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PLUME TEMPERATURE MEASUREMENTS OF SHALLOW, SUBMERGED MODEL DISCHARGES WITH CURRENT

L. D. Winiarski, et al

Pacific Northwest Environmental Research Laboratory
Corvallis, Oregon

January 1973

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By

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Program Element 1B1032

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ABSTRACT

Laboratory studies were conducted with a shallow-submerged thermal discharge model in a flowing ambient stream. Plume behavior, characterized by excess temperature, trajectory, and width, was observed to determine the qualitative effects of the discharge angle, Froude number, relative stream velocity, and turbulence in the ambient water.

Increasing the angle of discharge in a vertical plane parallel to the direction of stream flow, caused increased dilution and lower temperatures along the trajectory. Jets of higher Froude number diluted less than those of lower Froude number for the same discharge angle and relative stream velocity. With no turbulence in the ambient stream, dilution was increased by a reduction in the ambient stream velocity. However, in a turbulent stream, dilution was decreased by a reduction in the ambient velocity.

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SECTION I

CONCLUSIONS

1. For the range of experimental variables in the reported program, jet dilution was increased (i.e. centerline excess temperature ratio decreased) as the discharge angle was increased with respect to the horizontal (coflow) configuration. For the horizontal discharge perpendicular to the ambient current (normal), plume temperatures at a given downstream location were usually between those of the vertical (90°) and the 15° discharges of the same Froude number (F) and the same ratio of jet velocity to stream velocity (k).

2. For jets of the same discharge angle and velocity ratio (k), decreasing the Froude number caused centerline excess temperature ratio to decrease more rapidly with respect to distance. Decreasing the Froude number also caused more rapid plume rise with respect to distance.

3. With the exception of the normal discharge, decreasing the ambient velocity in a non-turbulent field promoted dilution of jets with the same Froude number and discharge angle. Decreased ambient velocity also resulted in more rapid plume rise.

4. In general, turbulence in the ambient stream caused a reversal of the relationship between ambient velocity and temperature. With turbulence, decreasing the ambient velocity resulted in less dilution.

SECTION II

RECOMMENDATIONS

1. In order to promote the most rapid mixing, it is recommended that effluent nozzles discharge at large angles relative to the river bottom and the direction of stream flow.

2. In as much as the largest temperature drop occurs in the immediate vicinity of the nozzle and this temperature drop is greater when there is large angular deviation between the nozzle and the stream, it is recommended that more study be devoted to understanding and predicting the initial mixing in this region.

3. This program was limited to laboratory models and a narrow range of parameters. Where possible these results need to be compared with other laboratory studies and field data.

4. In order to show a more significant effect of turbulence, it is recommended that turbulence be generated on a scale large enough to actually fluctuate the plume trajectory.

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SECTION III

INTRODUCTION

One of the primary means of waste heat disposal available to the electric power generating industry and other industries is the direct discharge of heated cooling water to the aquatic environment. Although such disposal schemes may be economical from the standpoint of capital costs and operating expenses, once-through cooling may create a thermal pollution problem in the receiving water body. This potential problem can be minimized through proper design of the effluent outfall and diffuser so that the heated water is adequately mixed and diluted with the ambient water. Details affecting this design are the depth of the receiving water body and the location of the discharge port relative to the water surface and/or bottom.

With respect to these factors, diffuser design and evaluation has been categorized as either submerged or surface. In the former, the diffuser is located at a depth where the effects of boundary conditions are assumed negligible or nonexistent. With the latter, the diffuser is located at the water surface and produces a layer of relatively high temperature water above the colder unmixed water. Shirazi and Davis (1972) have evaluated and combined predictive models for the analysis of submerged diffusers. Their work is presented in the form of nomograms that provide estimates of the physical spread and temperature distribution of a discharge plume. Work of a similar nature is being advanced with respect to surface discharges.

There is, however, an intermediate situation, that of a shallow submerged diffuser, wherein the discharge port is located on or near the bottom of a shallow water body. Located as such, the plume temperature and

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trajectory may be influenced by the bottom, the water surface, or a combination of those two boundaries. The condition of shallow submergence has numerous examples where a diffuser pipe is located on a river bottom. Because of the uncertainty of predictive methods and scarcity of experimental data relative to the shallow submergence situation, predesign analyses and diffuser performance estimates are limited. This study was undertaken to provide information on the behavior of shallow submerged jets. The data in this report can be used for the purpose of verifying analytical models as they are developed. A future laboratory study dealing with deeply submerged discharges will compare laboratory data with existing analytical models.

Plume behavior is usually characterized in terms of its trajectory, width, and temperature distribution along the trajectory. In this report trajectories are plotted with respect to vertical and horizontal coordinates, made dimensionless by dividing by the discharge nozzle diameter. Plume widths along the trajectory are made dimensionless in a similar manner. Temperatures along the trajectory are expressed as the ratio of the excess temperature at a point to the excess discharge temperature. The temperature excess is with respect to the temperature of the ambient water body.

The primary objective of the study was to determine qualitatively how the plume characteristics of temperature, trajectory, and width are affected by the different parameters which influence these characteristics. These parameters include:

1. the angle of discharge with respect to the ambient current;

2. the ratio (k) of the jet velocity (U_j) to the ambient velocity (U_a);

3. the turbulence level of the receiving stream; and

4. the Froude number (F).

The Froude number is defined as $F = \frac{U_j}{\sqrt{\frac{\Delta\rho_o}{\rho_o} gD}}$ where D is the nozzle diameter, $\frac{\Delta\rho_o}{\rho_o}$ is the normalized excess density, and g is the gravitational constant. Other factors to be considered include:

5. the depth of the water body and
6. the existence of any temperature (density) gradient.

To study the above relationships, experimental parameters were chosen to facilitate measurement and duplication in the laboratory. In all cases, the ambient water body was isothermal and ten diameters in depth and the discharge port was located on the bottom. Two jet/ambient velocity ratios (k) were selected: k=2 and k=6. Similarly, two Froude numbers were evaluated: F=12 and F=37. The two jet velocities of one (1) and three (3) feet per second provided Reynolds numbers greater than 5,000. Four different discharge angles to the direction of flow were studied. Measured from the horizontal, these are 0° (coflow), 15°, 45°, and 90° (vertical). Additionally, a horizontal discharge normal to the direction of the ambient current was studied. With respect to turbulence, plume behavior was examined under two conditions: in the absence of any turbulence and in the presence of an artificially generated turbulence. Combinations of the previously described parameters provide a total of forty different test conditions (see Table 1) from which qualitative conclusions are drawn.

The conditions in the laboratory do not necessarily represent any field situation. However, they do represent typical parameters that might be encountered in the field. These conditions were selected so that trends predicted by analytical models could be checked against laboratory conditions.

One should be cautioned about using the reported data as design criteria inasmuch as several important conditions which might occur in the field have been omitted from these experiments. For example, near a field installation, natural barriers may serve to limit the amount of ambient water available for dilution. The resulting recirculation would be difficult to quantify. Also, the single port nozzle configurations studied here do not represent best available techniques for maximizing the amount of heated water that can be discharged.

TABLE 1. Matrix of Experimental Parameters

			Discharge Angle				
			0°	15°	45°	90°	Normal
No Turbulence	F=12	k=2	Fig. Nos. 4 12	4 12	4 12	4 12	4 20
		k=6	6 14	6 14	6 14	6 14	6 20
	F=37	k=2	5 13	5 13	5 13	5 13	5 20
		k=6	7 15	7 15	7 15	7 15	7 20
With Turbulence	F=12	k=2.7	8 16	8 16	8 16	8 16	8 21
		k=7	10 18	10 18	10 18	10 18	10 21
	F=37	k=3	9 17	9 17	9 17	9 17	9 21
		k=8	11 19	11 19	11 19	11 19	11 21

SECTION IV

EXPERIMENTAL METHODS

Experiments reported herein were conducted in a towing channel forty (40) feet long and two (2) feet wide. The discharge nozzle and a simulated river bottom were suspended from a carriage mounted on rails along the top of the channel (see Figure 1). The nozzle and attached bottom were towed through the water to obtain the desired relative velocity. The diffuser orifice was one-half inch in diameter. Heated effluent was discharged from a constant head tank which was also mounted on a carriage. This reservoir was periodically refilled with hot water from a constant temperature bath. Discharge velocities were controlled by valves at the effluent reservoir.

A third carriage supported the temperature transducer and cable. Transversing vertically through the discharge plume, the transducer monitored temperature profiles at predetermined distances downstream from the nozzle exit. The traversing mechanism was directly linked to the horizontal movement of the carriage through a simple pulley arrangement.

Because of its characteristics of fast response and verstility, the transducer selected was a hot film anemoneter. Signals were processed through a TSI Model 1050 anemometer and recorded on an XY recorder. To facilitate data reduction, an intermediate circuit was inserted between the signal processer and the recorder. This circuit allowed adjustment of the time response of the anemometer, analogous to increasing the thermal mass of the transducer, so that temperature oscillations were effectively averaged.

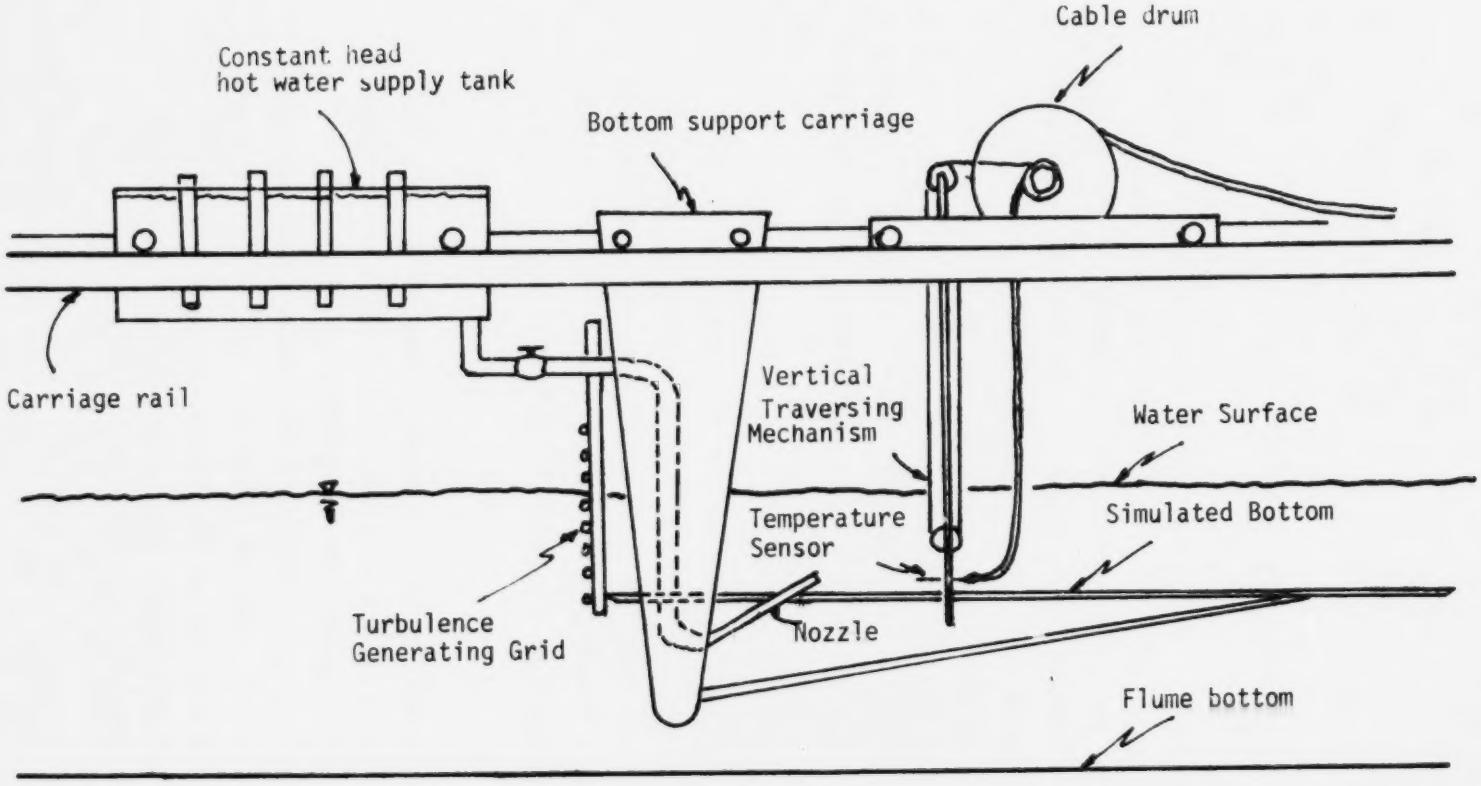

FIGURE 1. Experimental Apparatus

Test procedure entailed calibration of the recorder for temperature and position and adjustment of the discharge valves to attain the desired effluent flow rate (hence discharge velocity). With an attached chiller/boiler system, the water in the channel was brought to approximately 68°F (20°C). The constant head reservoir was then filled with heated effluent such that the excess temperature at the orifice would be approximately 30°F (16.7°C). Prior to each series of test runs the actual exit temperature was monitored with a Hewlett Packard Model 1801A quartz thermometer. The transducer carriage was then located at a predetermined distance from the orifice with the anemometer probe positioned near the simulated bottom. Next the nozzle was opened and the carriage assembly was towed through the channel at a uniform velocity. To insure accuracy and eliminate inconsistencies, the above procedure was repeated three times at each statior downstream from the nozzle. The stations at which the temperature profiles were recorded were at 10, 20, 30, 40, 60, and 90 nozzles diameters along the horizontal axis. An example of the data display is provided in Figure 2. For the case illustrated the discharge angle is 15°, the Froude number is twelve (12), the discharge velocity to ambient velocity ratio (k) is two (2) and the damping of the transducer signal is minimal.

Figure 2 also illustrates the effect of ambient turbulence. To qualitatively determine the effect of turbulence levels in the receiving stream, turbulence was generated by a removable grid ahead of the discharge nozzle (see Figure 1). The grid was made of three-eighths inch (3/8 inch) round bars spaced at one inch on center.

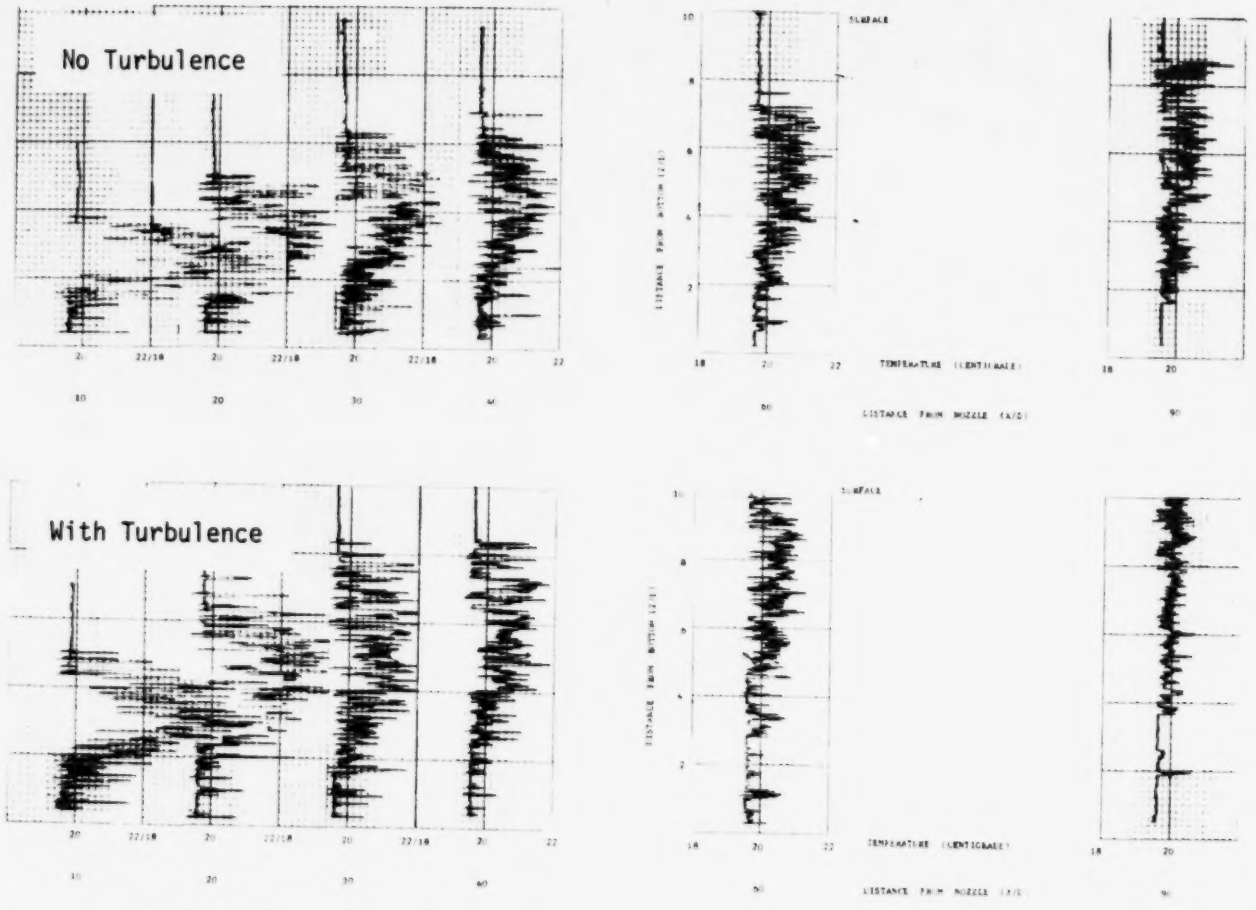

FIGURE 2. Typical temperature traverses: θ=15°, F=12, k=2.

So that data collected in this study might properly be interpreted and compared with other data, an effort was made to quantify the turbulence generated by the grid at different towing velocities. For that purpose the anemometer was calibrated and used in the velocity mode. The turbulent velocity fluctuations behind the moving grid were then monitored and passed through a TSI Model 1060 RMS voltmeter. Despite the fact that it was difficult to differentiate between oscillations introduced by the carriage movement and the true turbulent fluctuations, some quantitative observations were made. In general, the carriage oscillations produced an apparent turbulence intensity (i.e. ratio of the root-mean-square of the velocity fluctuations to the mean velocity) on the order of six percent (6%). The turbulent intensity behind the moving grid was on the order of 9 percent at all stations for the different towing velocities.

An additional problem introduced by the grid, however, was its effect on mean velocities. By its arrangement, the grid presented a blockage for flow over the simulated bottom and forced a portion of the water mass to move beneath the bottom. As a consequence, the relative velocity of the water body behind the grid differed from that of the carriage. The velocity correction curve is shown in Figure 3. The significance of this is that for the same carriage velocity, the corresponding k ratios for the conditions of "no turbulence and "turbulence" are different and direct comparisons are difficult.

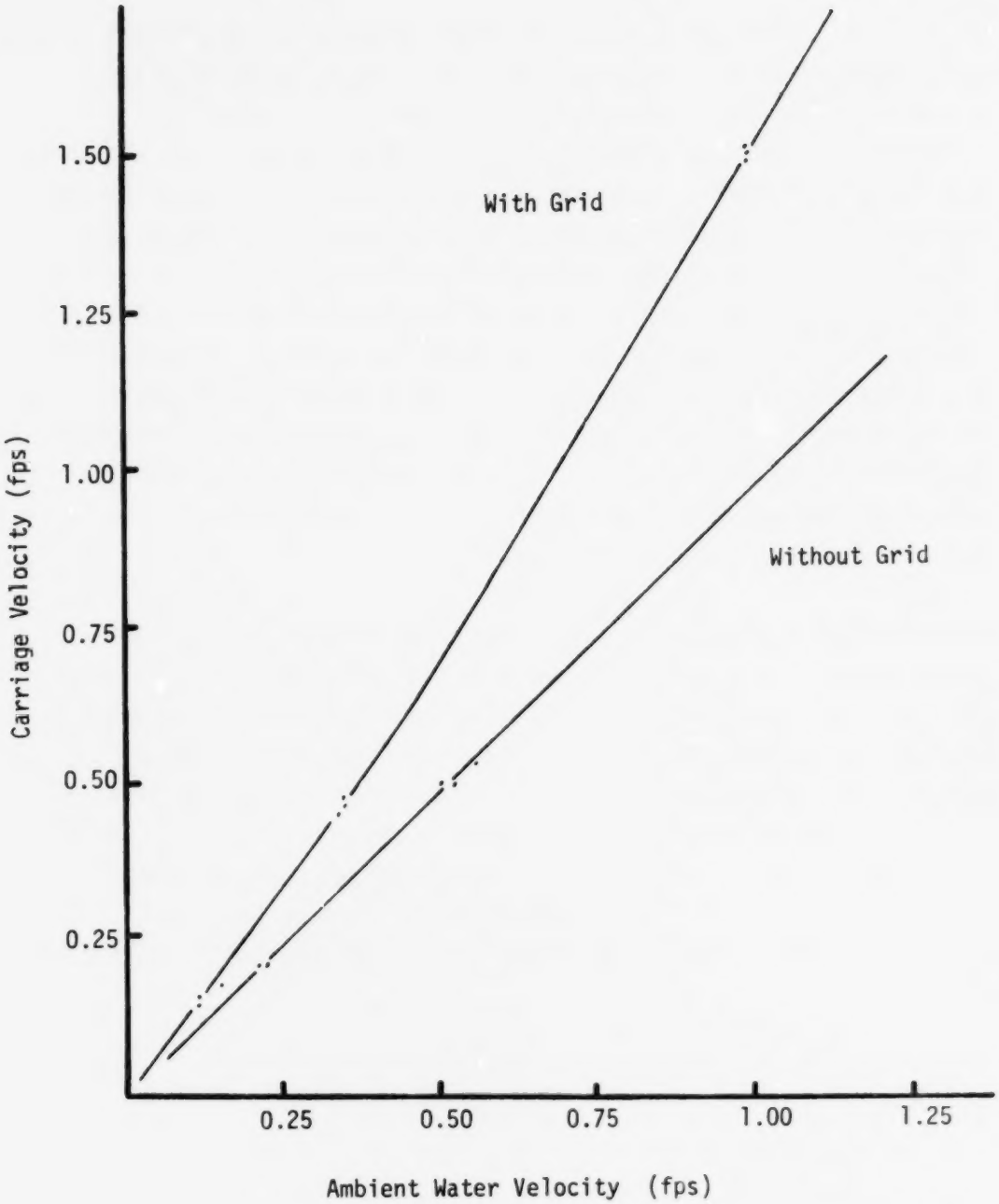

FIGURE 3. Water Velocity Behind Towed Grid as a Function of Carriage Speed

SECTION V

RESULTS

Plume behavior is usually characterized in terms of its trajectory, width, and temperature distribution along the trajectory. In this report trajectories are plotted with respect to vertical and horizontal coordinates, made dimensionless by dividing by the discharge nozzle diameter. The trajectory is delineated by the vertical location of peak temperatures along the horizontal axis. Vertical plume widths along the trajectory are made dimensionless in the same manner. Temperatures along the trajectory are expressed as the ratio of the excess temperature at a point to the excess discharge temperature. The temperature excess is with respect to the temperature of the ambient water body. Algebraically that is:

$$\frac{\Delta T_c}{\Delta T_o} = \frac{T_c - T_o}{T_j - T_o}$$

where T_j is the discharge temperature; T_o is the ambient temperature; and T_c is the temperature in the plume at point c.

When the above mentioned characteristics of temperature $(\frac{\Delta T_c}{\Delta T_o})$, vertical trajectory $(\frac{Z}{D})$, and width $(\frac{W}{D})$ are plotted versus the horizontal distance from the jet $(\frac{X}{D})$, a description of the plume is obtained. Test results are presented in terms of how these plume characteristics are influenced by the previously discussed parameters: configuration (θ); Froude number (F); relative velocity ratio (k); and turbulence.

Jet Configuration

The greatest influence on plume characteristics was exerted by the jet configuration, i.e., the angle of discharge relative to the ambient

current. Neglecting temporarily the horizontal discharge perpendicular to the angle of flow (normal), Figures 4 through 7 show that larger discharge angles increased the plume dilution. The same result was obtained in a turbulent stream (see Figures 8 through 11). The normal configuration, discharging across the flow at zero angle relative to the bottom, diluted at a rate which was often intermediate between a high angle (90°) discharge and a lower angle (15° or coflow) discharge.

Figures 12 through 15 show the trajectories of the peak temperatures for the various test conditions without turbulence. Portions of the temperature decay curves are superimposed on the trajectories. Small deviations from the coflow configuration have a greater effect on the trajectory (and plume temperature) than do similar deviations from 90°. It is suspected that this result is related to the effect of the bottom which inhibits entrainment of the coflow plume from the underside. With approximately half of the effective dilution water eliminated, the plume attaches to the bottom. This results in low trajectories and high temperatures (Figures 4 to 7). When the discharge angle is increased slightly from horizontal, entrainment of ambient water is promoted. The same trend is again apparent in Figures 16 through 19 which are for conditions of a turbulent stream.

The peak temperature trajectories for the normal configuration are shown in Figures 20 and 21. Generally, the trajectories are low and flat, although not as low as with the coflow configuration. When the trajectories are compared with the temperature decay curves, it is apparent that the normal discharge is not influenced by the bottom. It is instead swept up and diluted near the source.

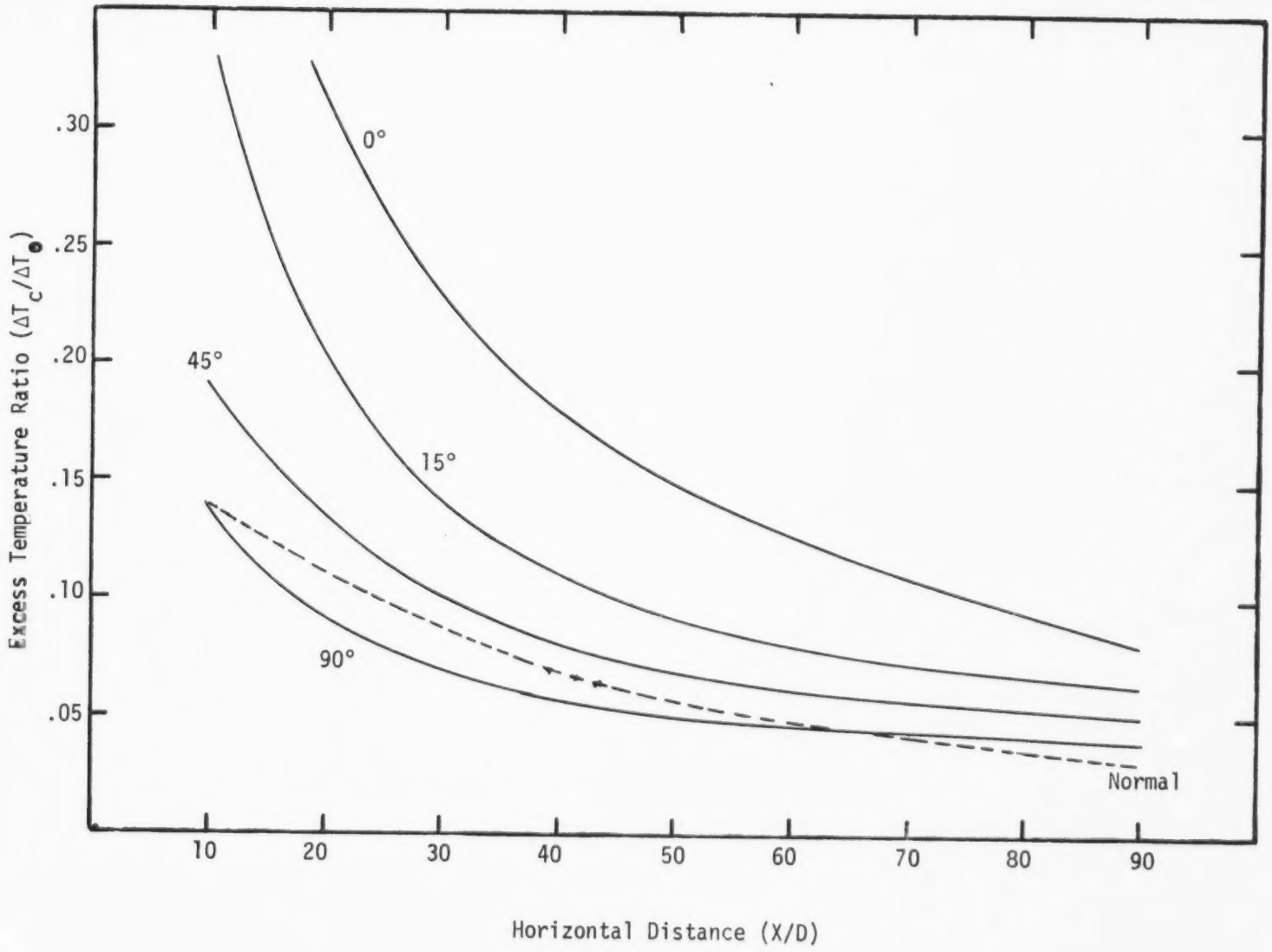

FIGURE 4. Temperature Decay Chart: No Turbulence, F=12, k=2.

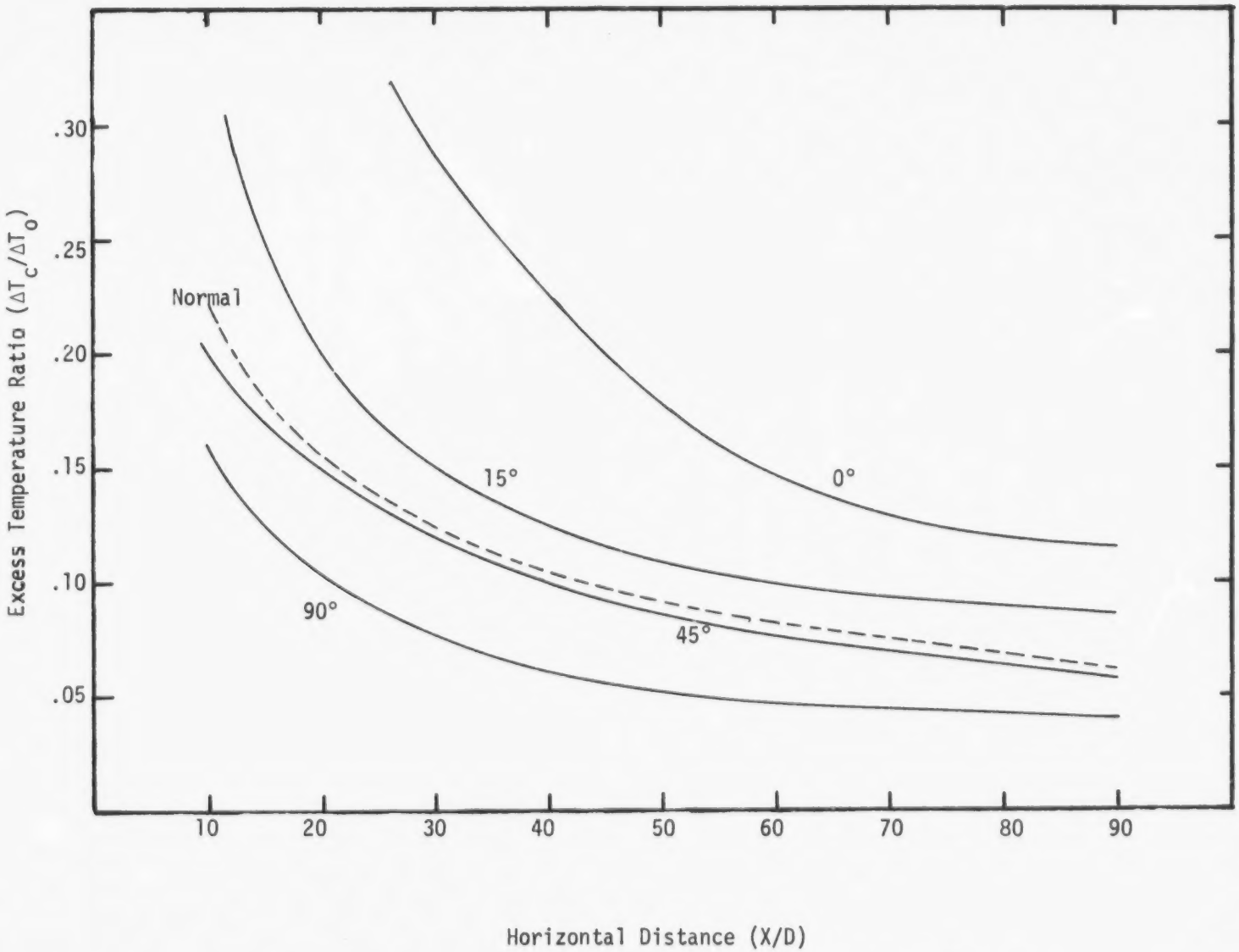

FIGURE 5. Temperature Decay Chart: No Turbulence, F=37, k=2.

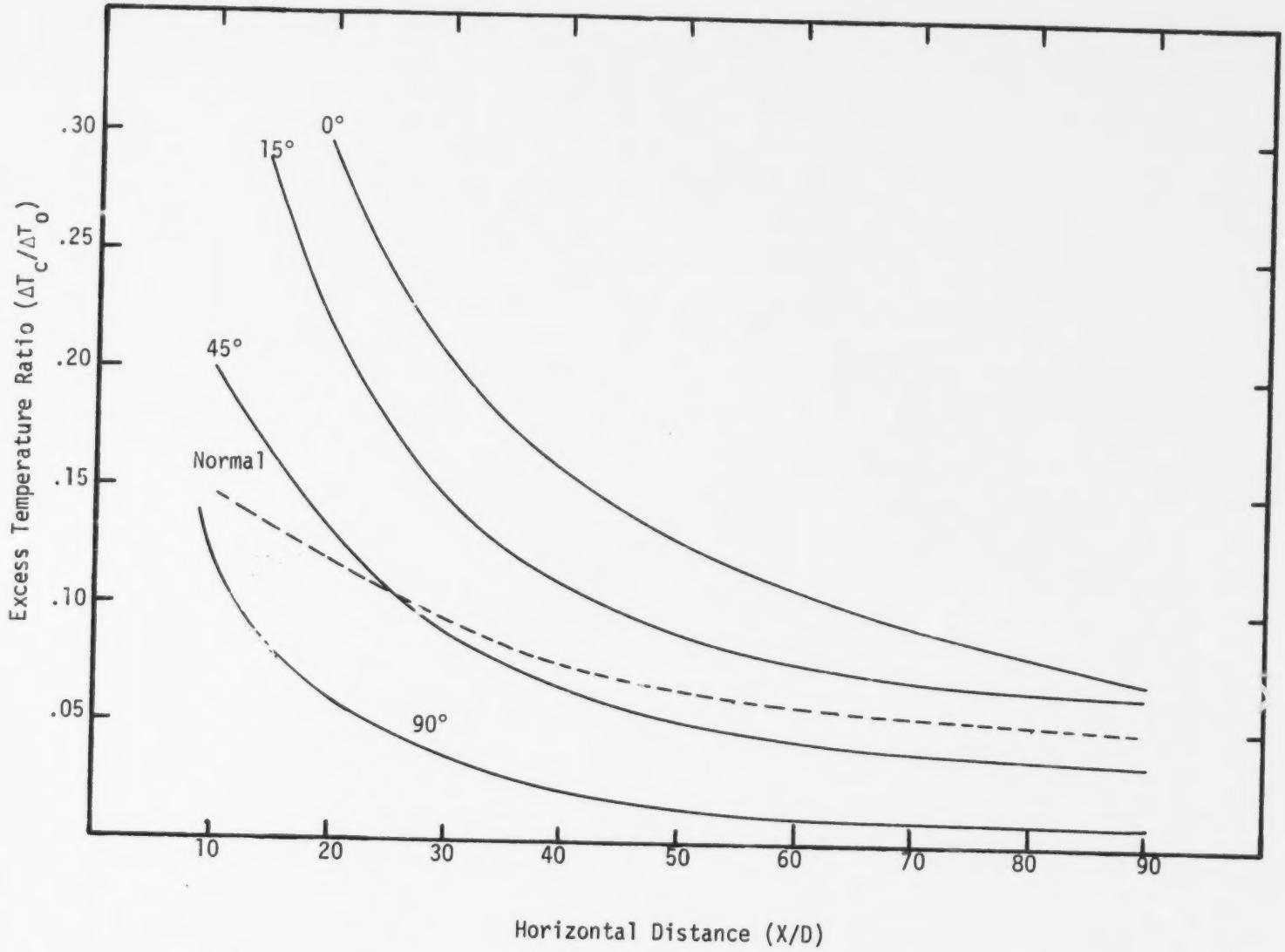

FIGURE 6. Temperature Decay Chart: No Turbulence, F=12, k=6.

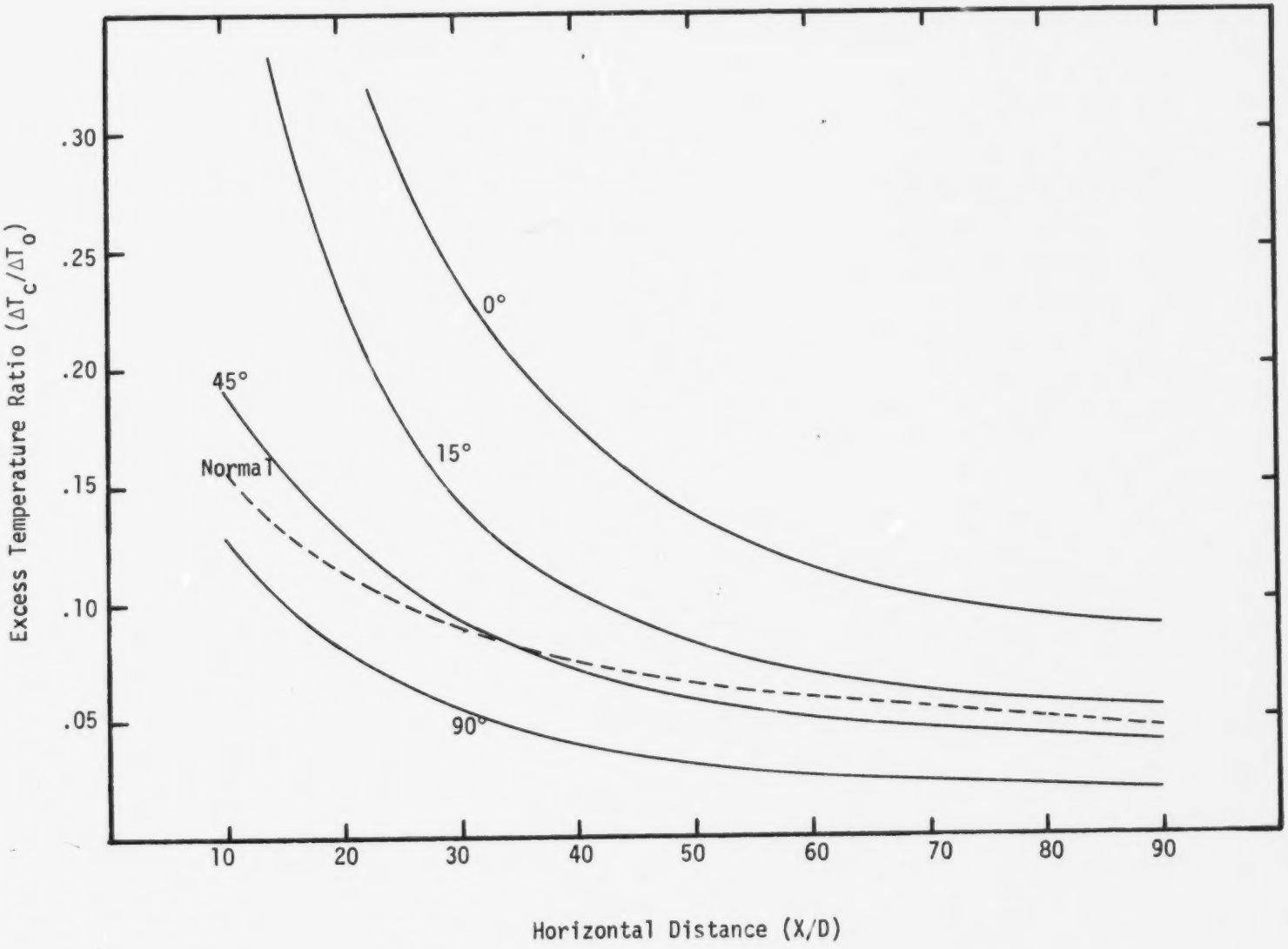

FIGURE 7. Temperature Decay Chart: No Turbulence, F=37, k=6.

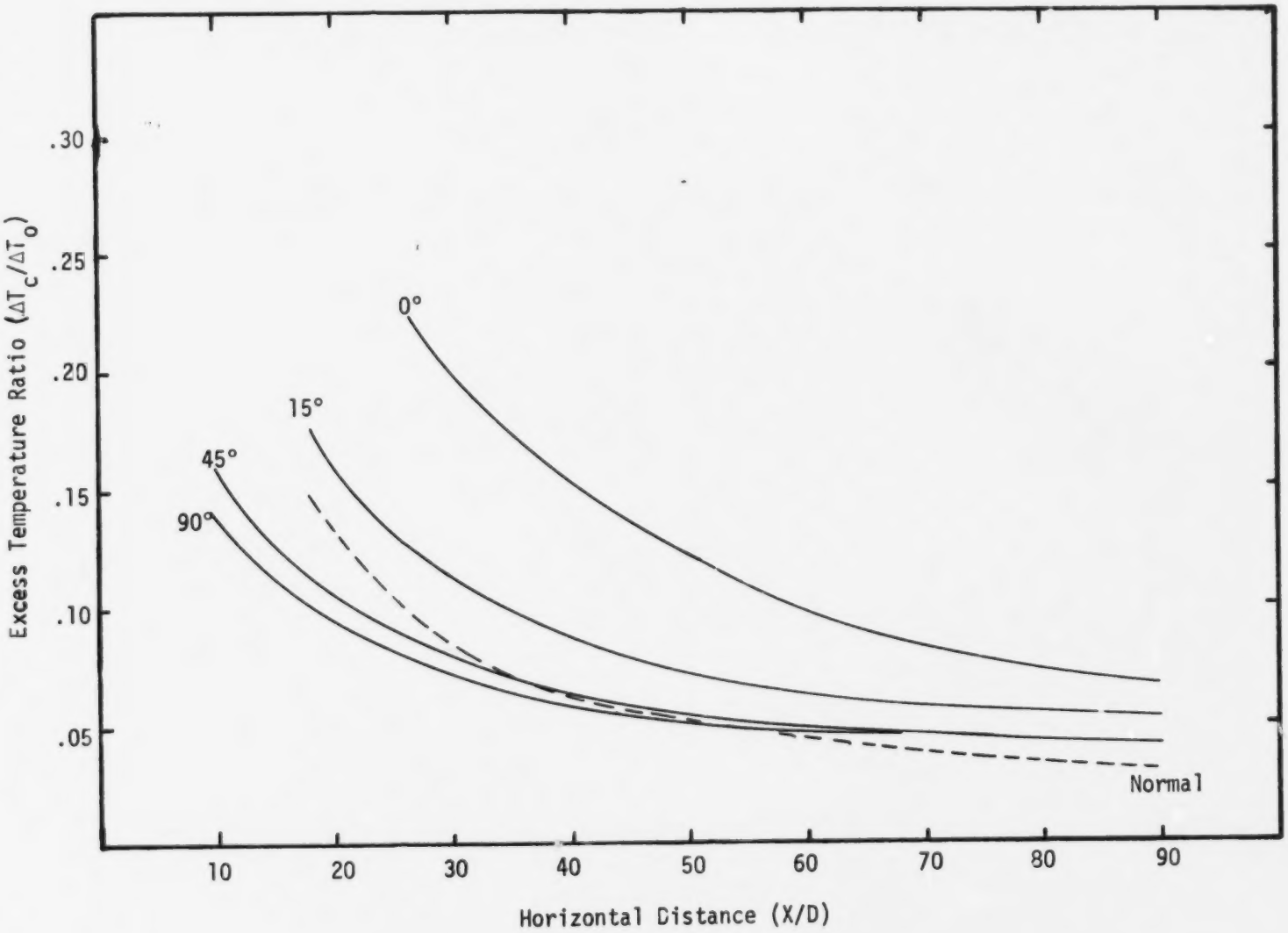

FIGURE 8. Temperature Decay Chart: With Turbulence, F=12, k=2.7.

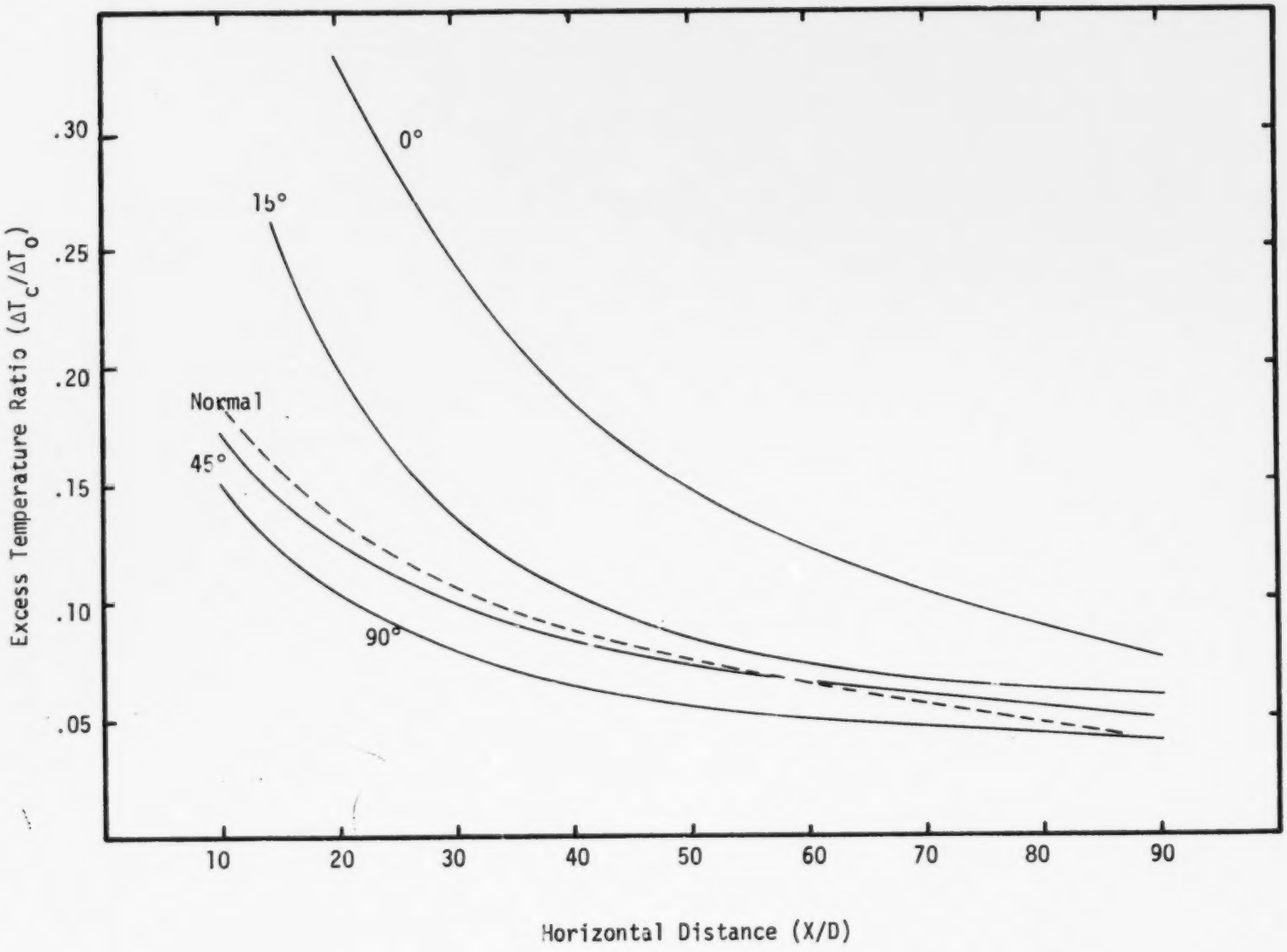

FIGURE 9. Temperature Decay Chart: With Turbulence, F=37, k=3.

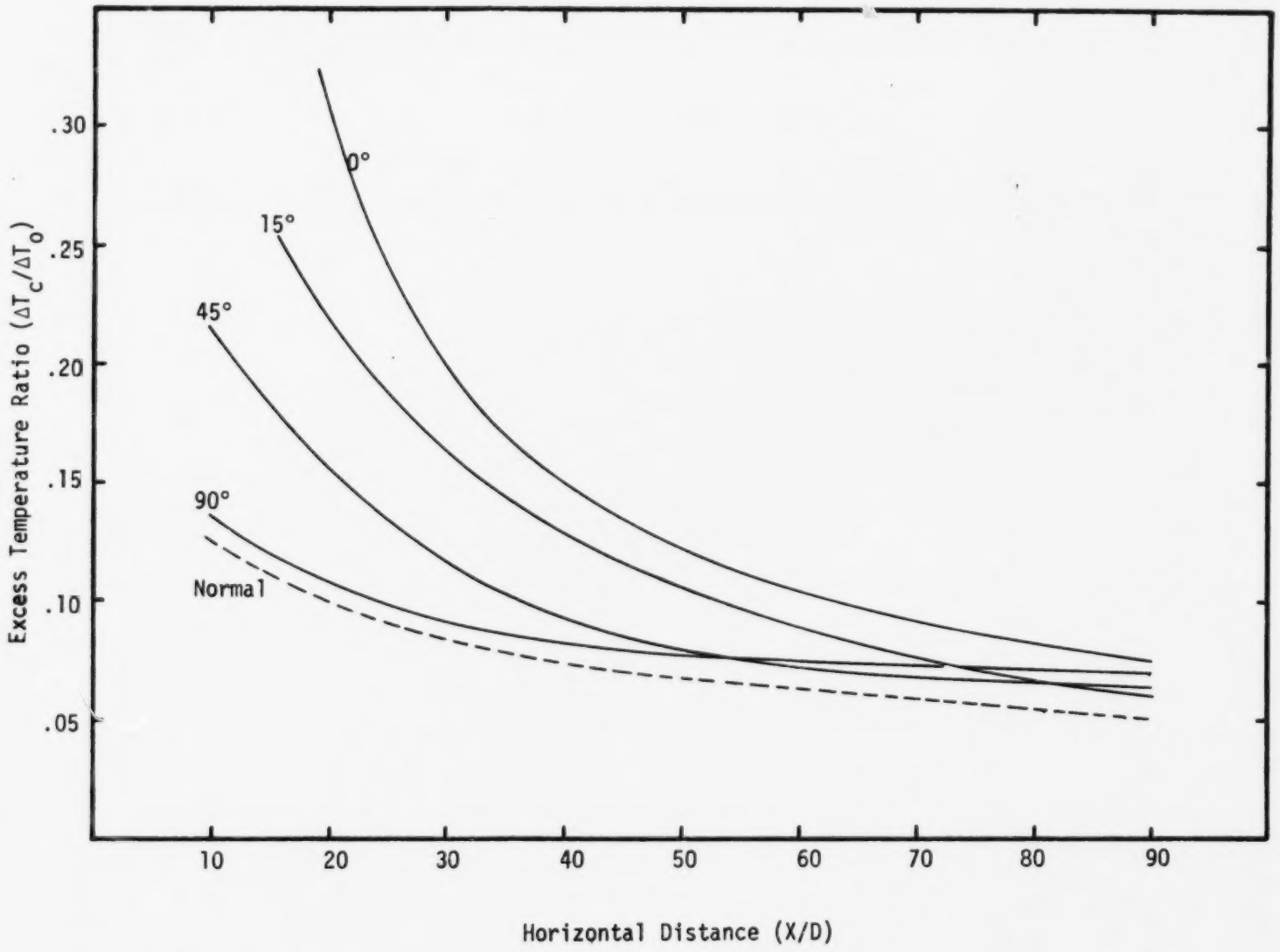

FIGURE 10. Temperature Decay Chart: With Turbulence, F=12, k=7.

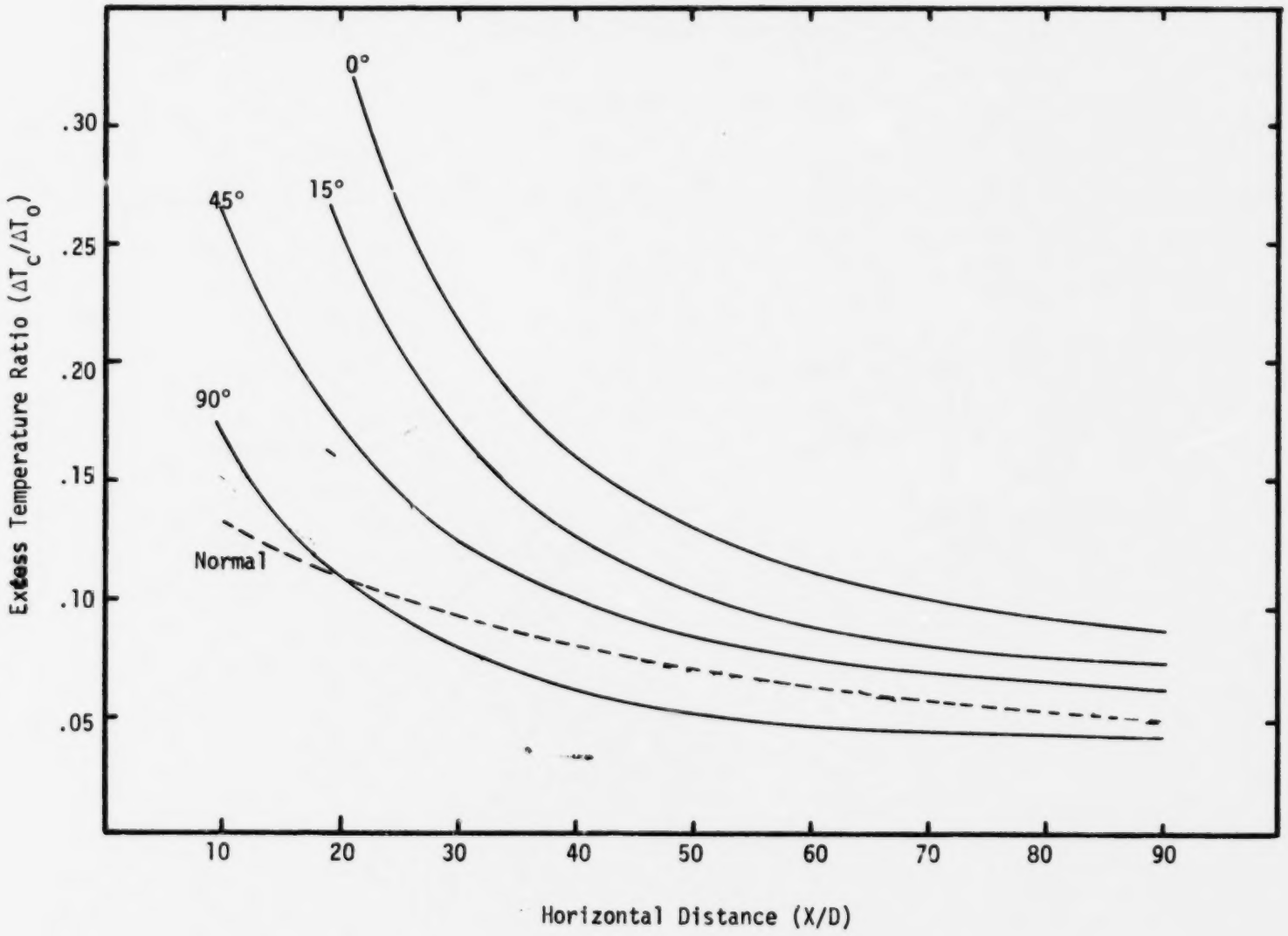

FIGURE 11. Temperature Decay Chart: With Turbulence, F=37, k=8.

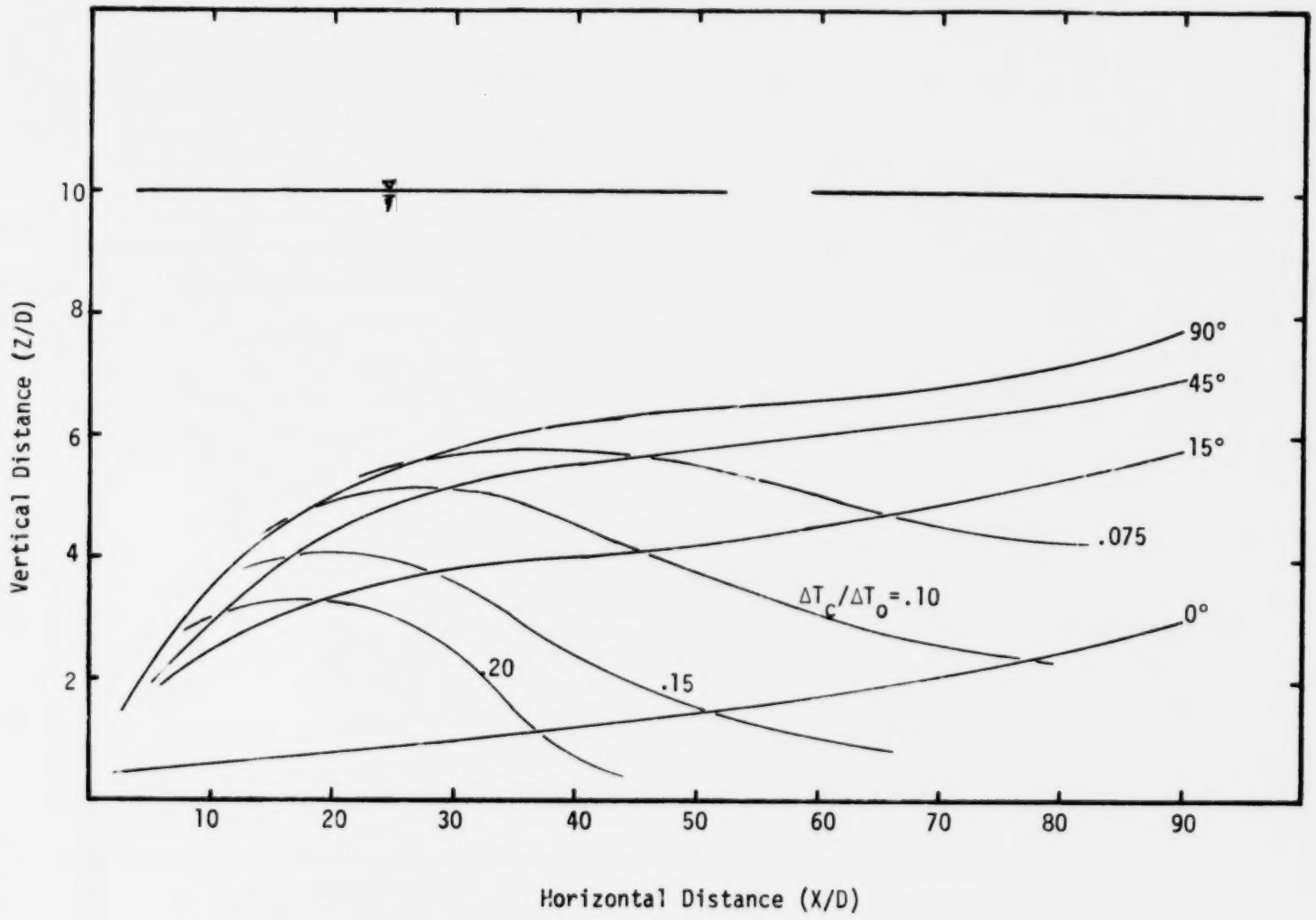

FIGURE 12. Trajectory - Temperature Chart, No Turbulence: F=12, k=2.

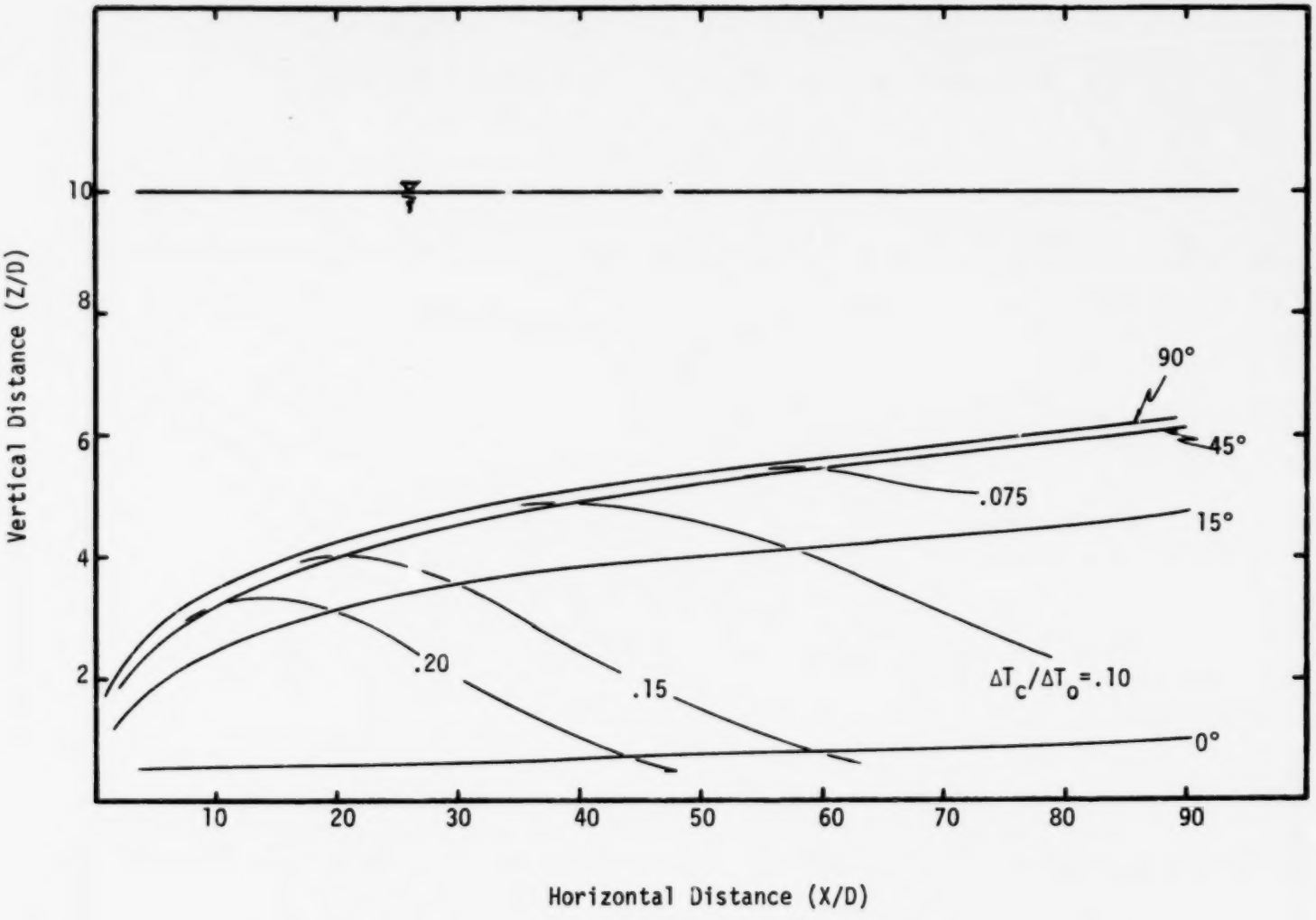

FIGURE 13. Trajectory - Temperature Chart, No Turbulence: F=37, k=2.

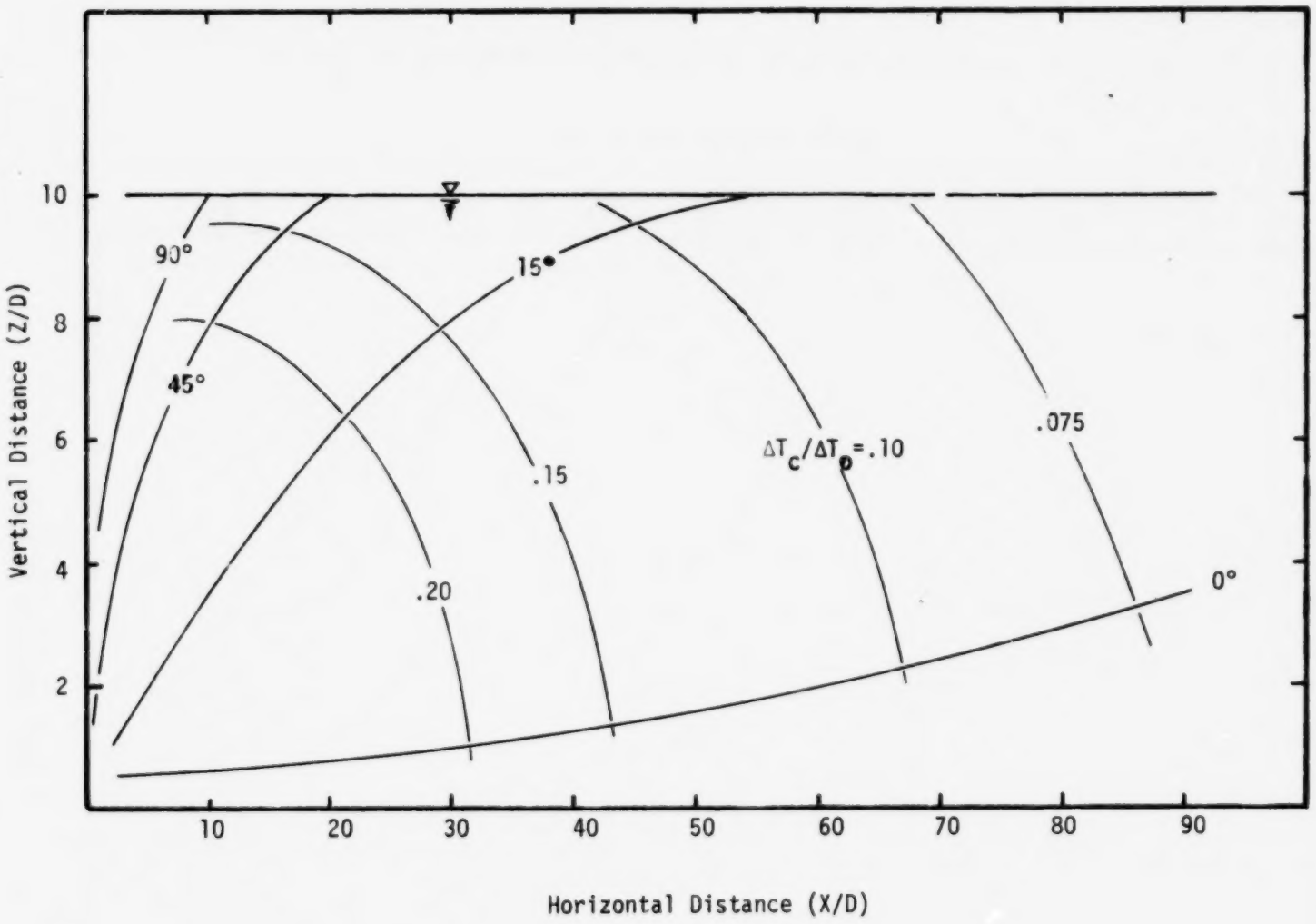

FIGURE 14. Trajectory - Temperature Chart, No Turbulence: F=12, k=6.

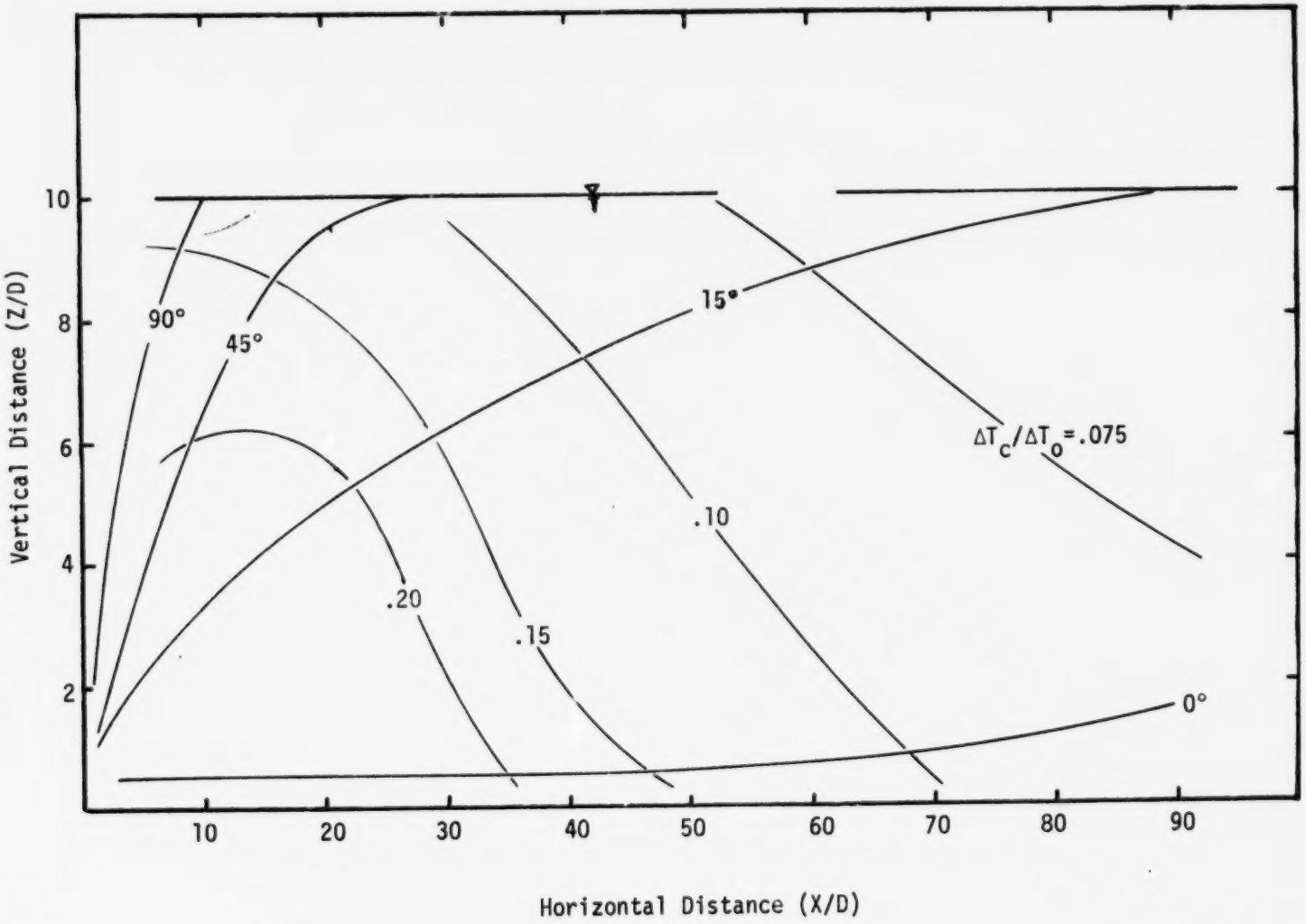

FIGURE 15. Trajectory - Temperature Chart, No Turbulence: F=37, k=6.

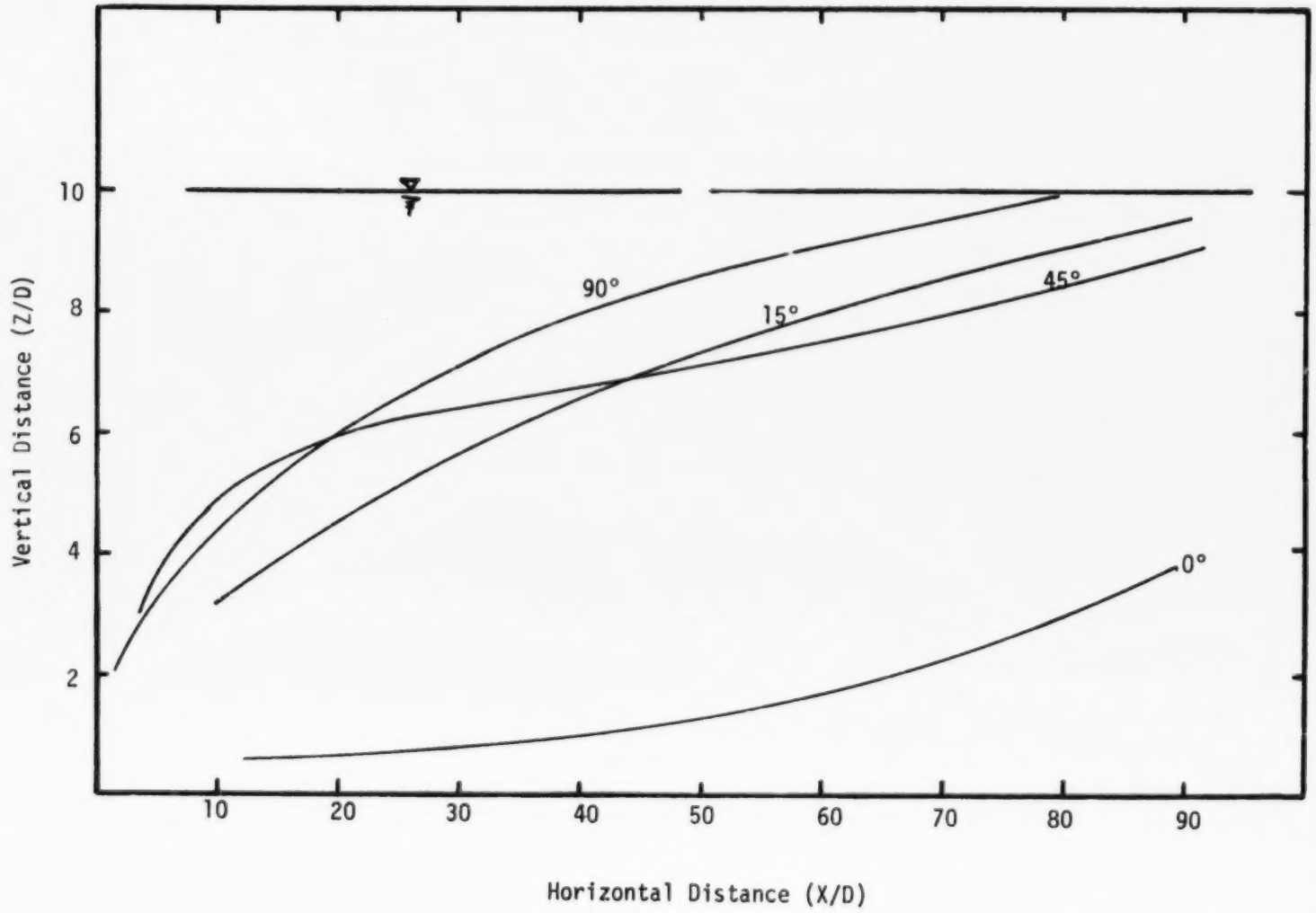

FIGURE 16. Plume Trajectory, With Turbulence: F=12, k=2.7.

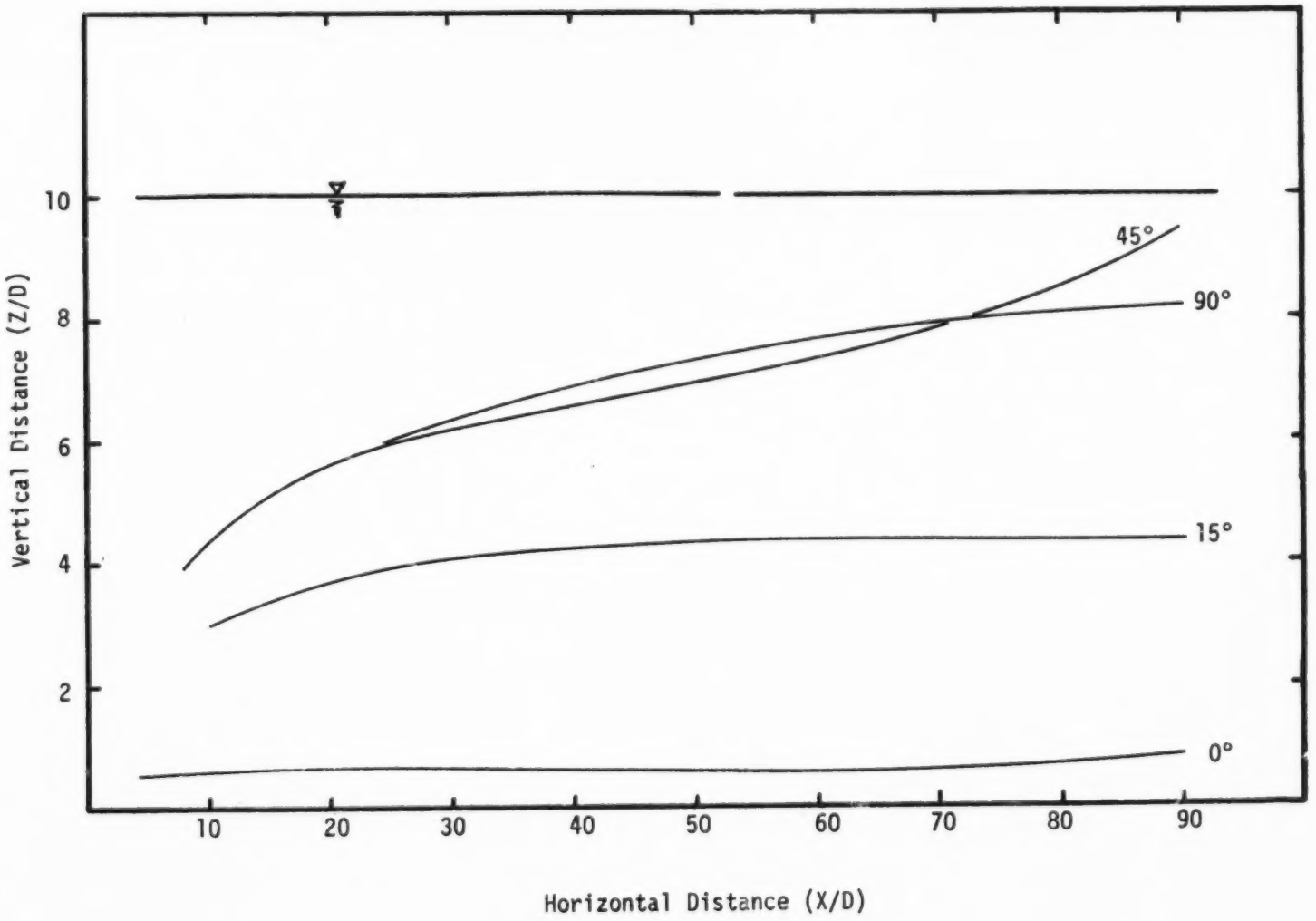

FIGURE 17. Plume Trajectory, With Turbulence: F=37, k=3.

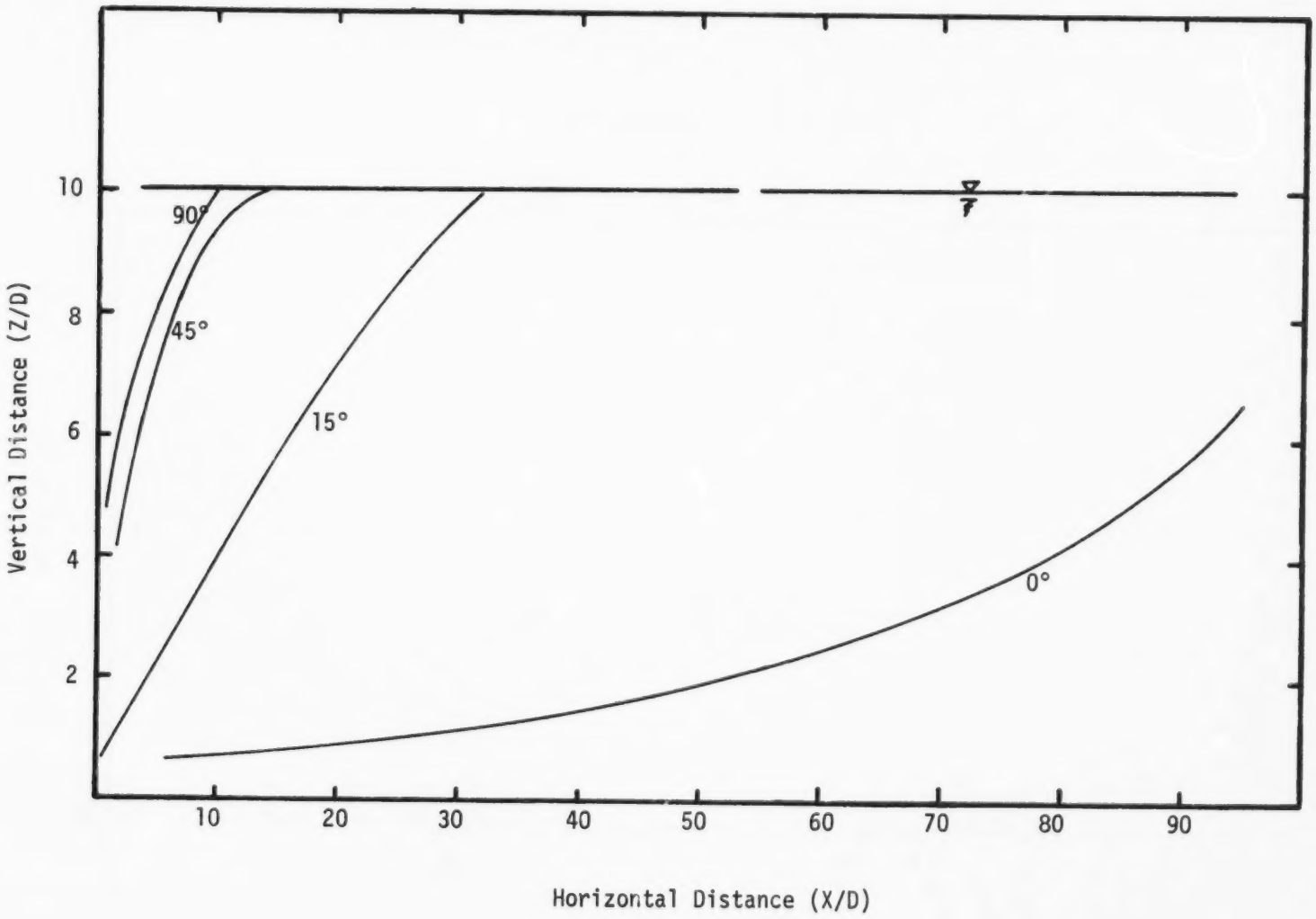

FIGURE 18. Plume Trajectory, With Turbulence: F=12, k=7.

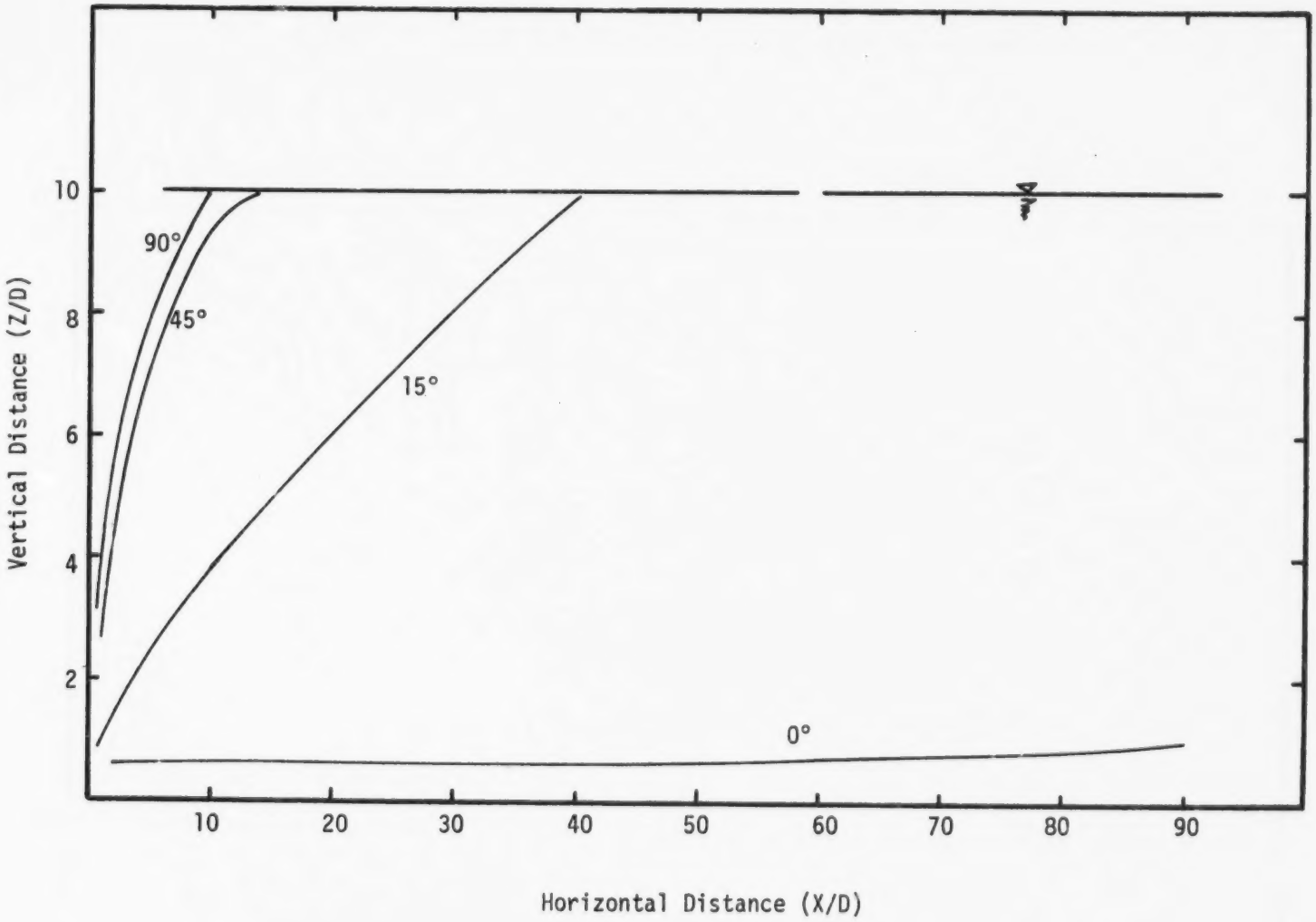

FIGURE 19. Plume Trajectory, With Turbulence: F=37, k=8.

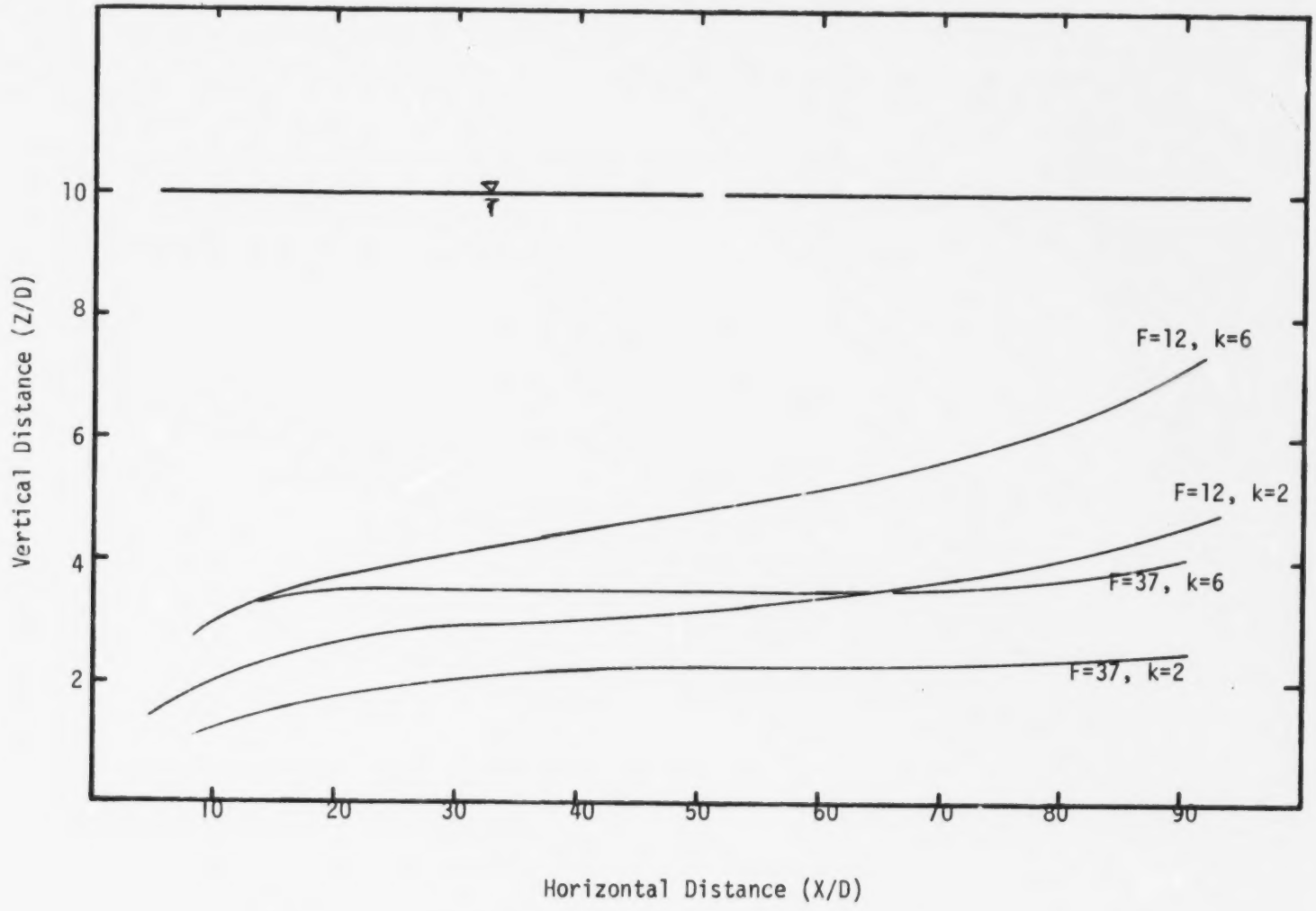

FIGURE 20. Plume Trajectory, Normal Configuration, No Turbulence.

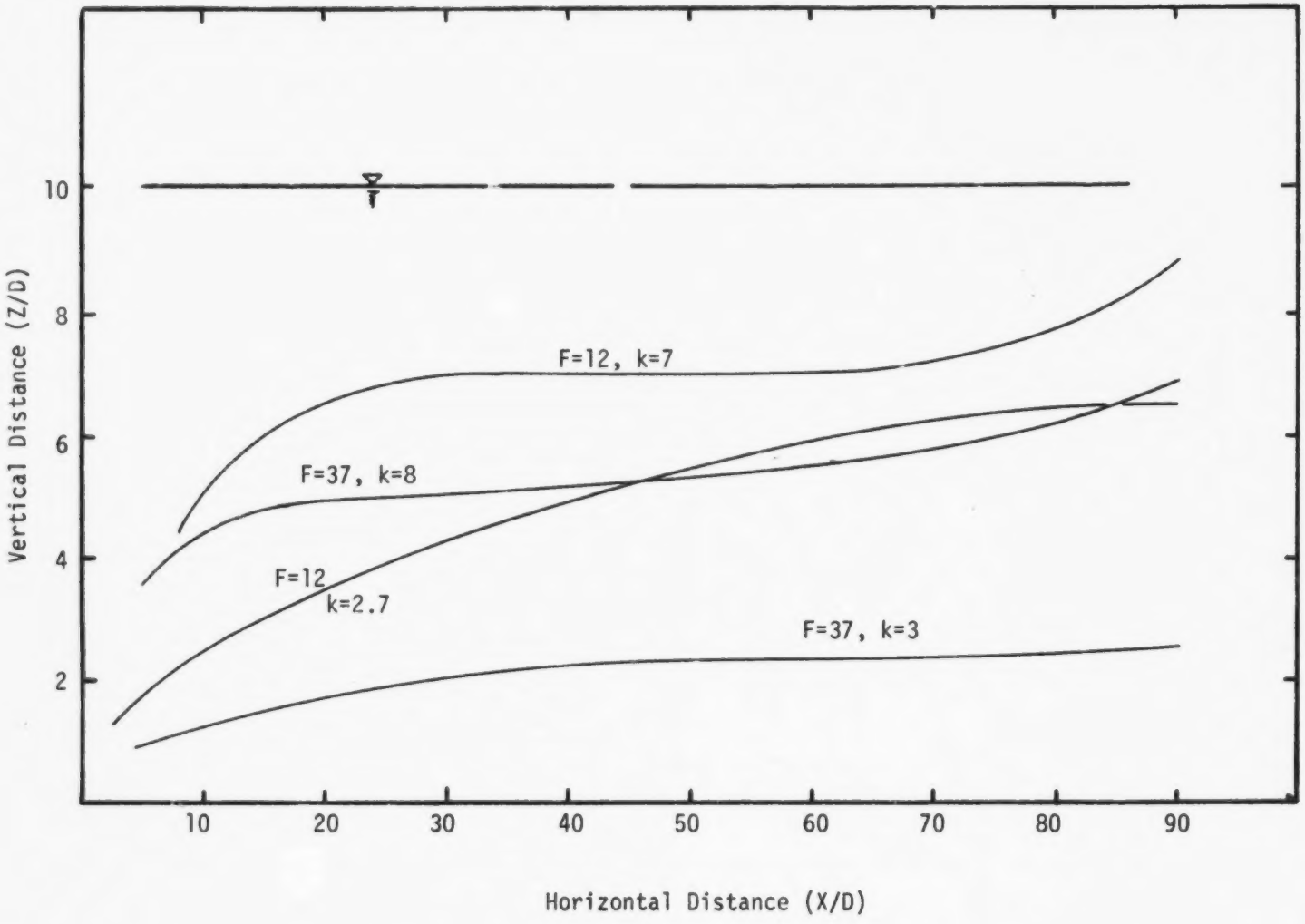

FIGURE 21. Plume Trajectory, Normal Configuration, With Turbulence.

For a given combination of k and F, plume widths were generally as dependent upon the boundary conditions as the discharge angle. Figure 22 illustrates plumes from two different discharge configurations, both with a k of 2 and Froude number equal to 12. The plume of the 45° jet is seen to be a bit wider and higher than that of the horizontal jet which is attached to the bottom. However, when the ambient velocity is reduced, such that K equals 6, the situation is reversed. Figure 23 shows that the coflow plume, still on the bottom, is wider than that of the 45° discharge which is a relatively narrow band at the surface.

Froude Number

The effect of the Froude number (F) on jet dilution was more subtle than the effect of discharge angle. Generally, the test results showed that the higher Froude number jets diluted less rapidly than those of a lower Froude number, irrespective of discharge angle. The result is more pronounced at higher relative velocities (lower k) than at the lower relative velocities. This is illustrated in Figure 24 for an angle of 45°. For k equal to 2, the lower Froude number jet has lower peak temperatures along the trajectory. At a k of 6 however, there is little difference between the plumes.

The same general relationship held true in conditions of turbulence although the data does not allow Froude number comparisons with the same relative velocity (i.e., F = 12, k = 7 is compared with F = 37, k = 8). Figure 25 illustrates this relationship for a jet angle of 45°. Additional comparisons for the Froude number effect can be made from the data in Tables A-1 through A-5.

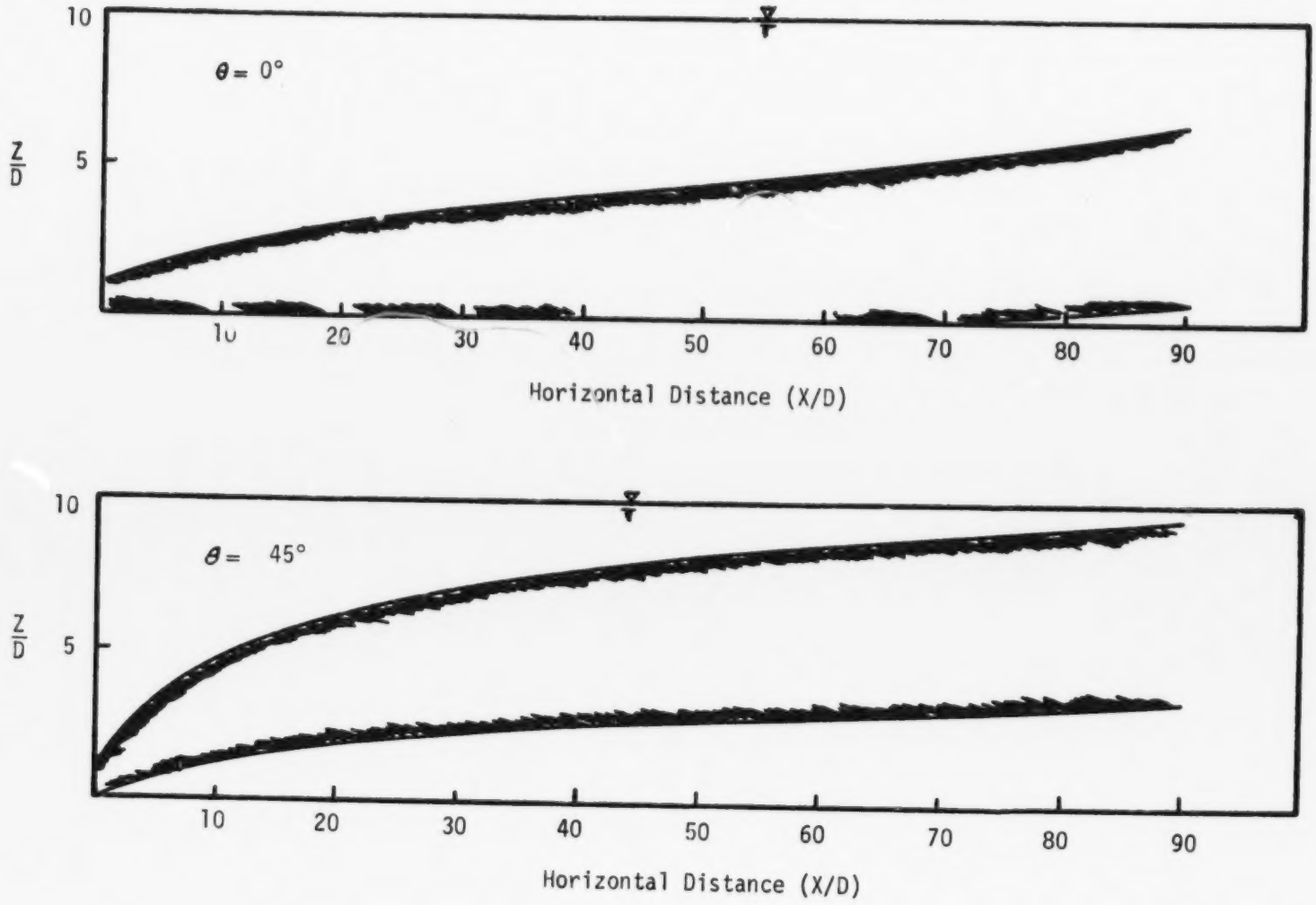

FIGURE 22. Effect of Discharge Angle on Plume Spread: F=12, k=2.

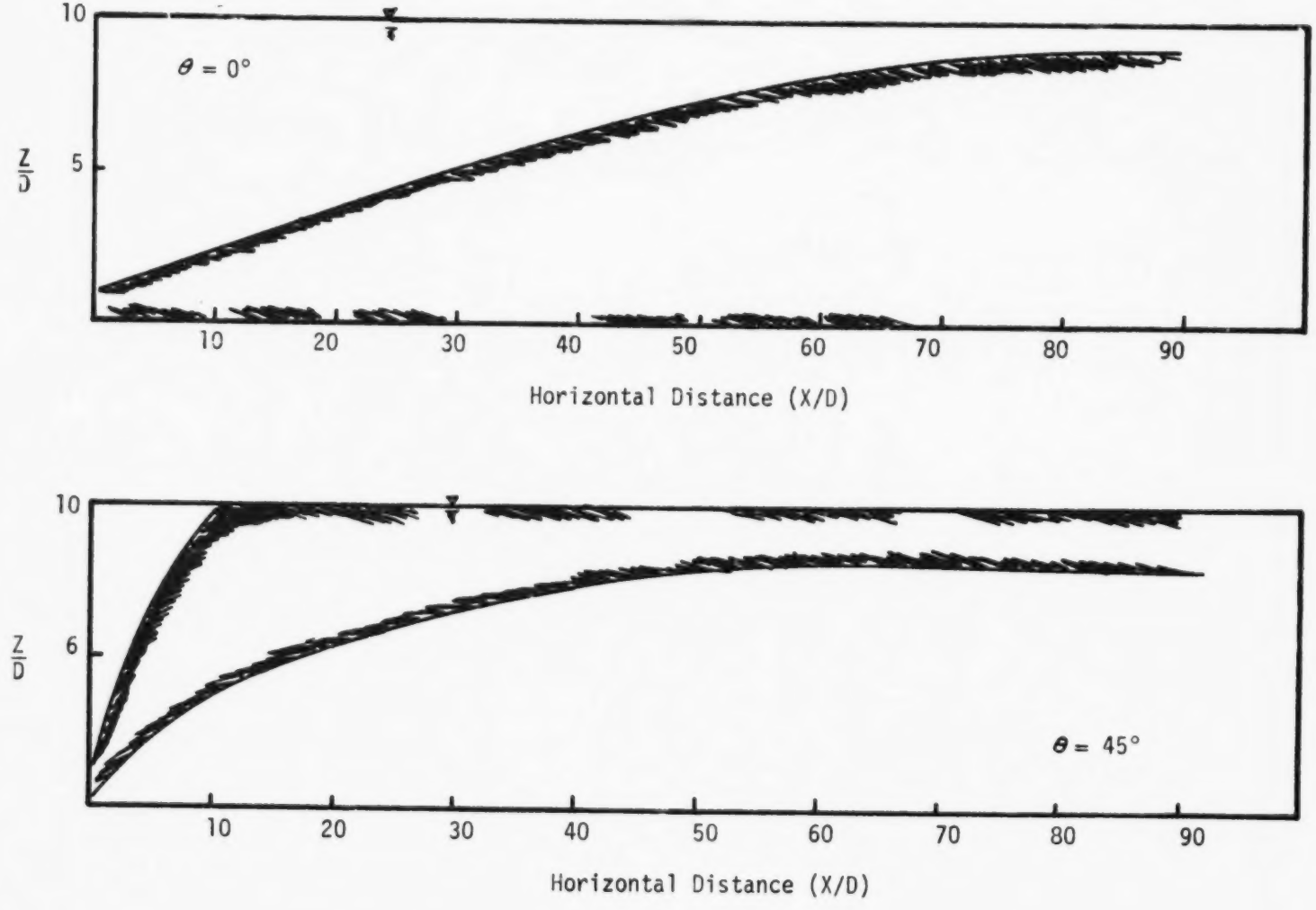

FIGURE 23. Effect of Discharge Angle on Plume Spread: F=12, k=6.

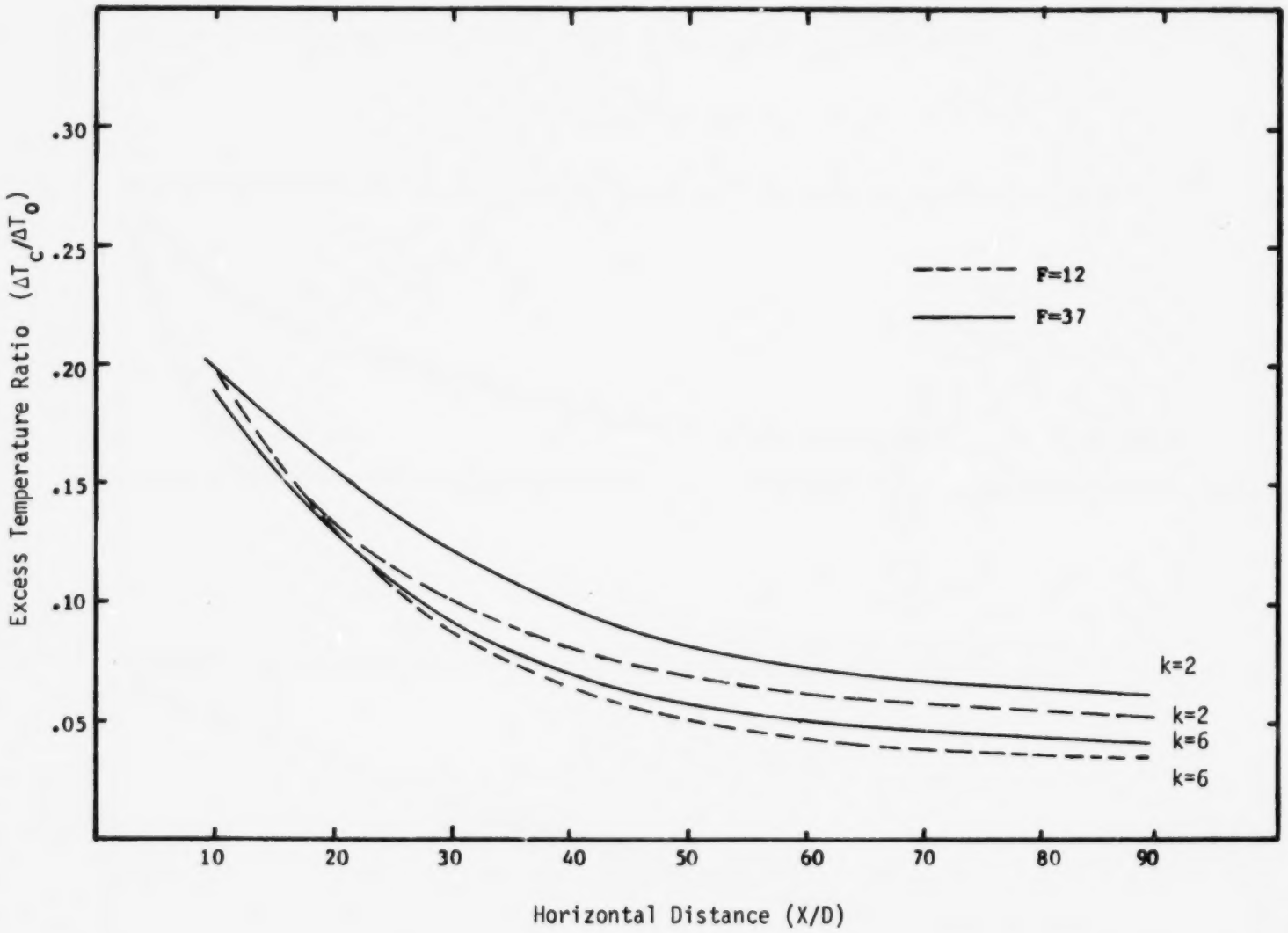

FIGURE 24. Temperature Decay Chart: Θ=45°, No Turbulence.

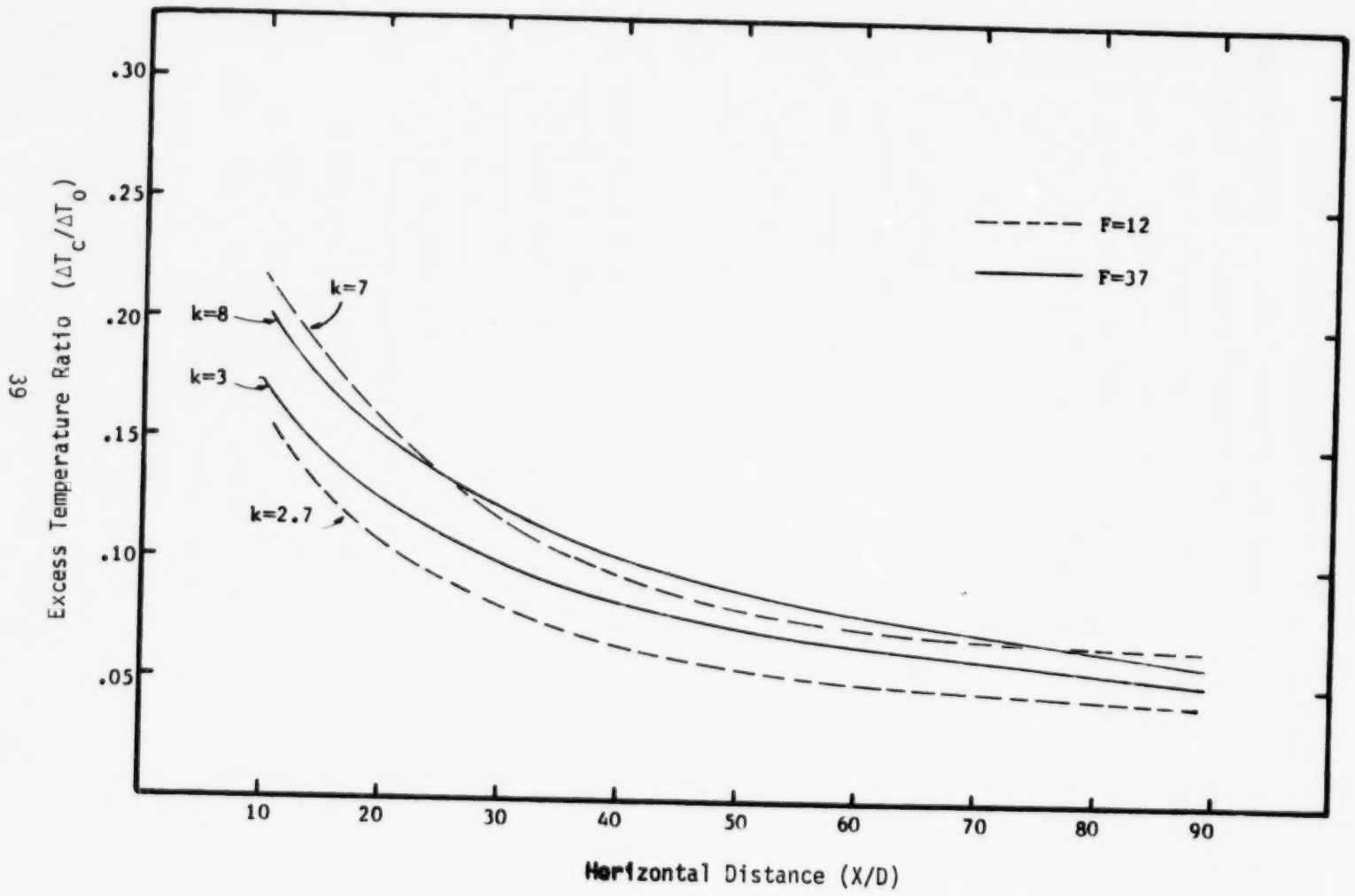

FIGURE 25. Temperature Decay Chart: Θ=45°, With Turbulence.

The peak temperature trajectories also demonstrated a slight Froude number dependency such that lower Froude number jets had a higher trajectory. This result may be seen by superimposing Figures 12 and 13, and Figures 14 and 15. The same result in a turbulent field is apparent in Figures 16 through 19. Froude number comparisons for the normal discharge angle are directly available from Figures 20 and 21.

Relative Velocity

When considered without turbulence, the velocity ratio had an inverse relationship to the plume temperature ratio: as k was increased, $\frac{\Delta T_c}{\Delta T_o}$ decreased. Again, using 45° as an example, Figure 24 shows this effect of k. At angles of 0°, 15°, and normal with F equal to 12, the temperature decay curves nearly overlap and the result is less apparent.

When turbulence was introduced, the above relationship appeared to be reversed in several instances. Figure 25 shows the temperature decay curves in a turbulent stream when the discharge angle is 45°. It can be seen that with both Froude numbers, higher velocity ratios are associated with higher plume temperatures. Because of the limited range of data, it is not known if this apparent reversal with turbulence is significant. Furthermore, an exception occurs at coflow where $\frac{\Delta T_c}{\Delta T_o}$ for the lower k is equal to or greater than for the higher k. Also, for the normal and 90° discharges, with F equal to 37, the excess temperature values are very nearly the same with both k's (refer to Tables A-4 and A-5).

A change in relative velocity has a more pronounced effect on trajectory than it has on the temperature decay. This is apparent from Figures 12 and 14, and Figures 13 and 15. As may be expected, the coflow trajectory is affected least by changing k.

Evaluating the effect of k on plume widths is complicated by the influence of the boundary surfaces. For example, Figure 26 shows the plume from a 15° jet with F equal to 37. With k = 6 (slower ambient velocity) the plume is much wider than when k = 2. For an angle of 45° (Figure 27) the vertical spread is restrained and the centerline widths of the two plumes are nearly equal.

Turbulence

As previously discussed, the effect of turbulence on plume behavior is difficult to isolate because of the different relative velocities. To adequately describe the influence of turbulence, plume temperatures for a given F and k in a non-turbulent medium must be compared with temperatures obtained in a turbulent field for a jet of the same F and k. Exact comparison can not be made with the data presented in this report. Approximations may be derived when a k = 2 is matched with a k = 3, and k = 6 is matched with k = 8 for F = 37. Similarly for F = 12, k = 2 is compared with k = 2.7 and k = 6 is compared with k = 7.

When caution is applied with respect to the above limitations, some generalizations may be made as to the effect of turbulence on this particular set of data. That is, for a given Froude number, at low k the temperatures in the non-turbulent stream were higher than those of the turbulent stream, while at the higher k the situation was reversed.

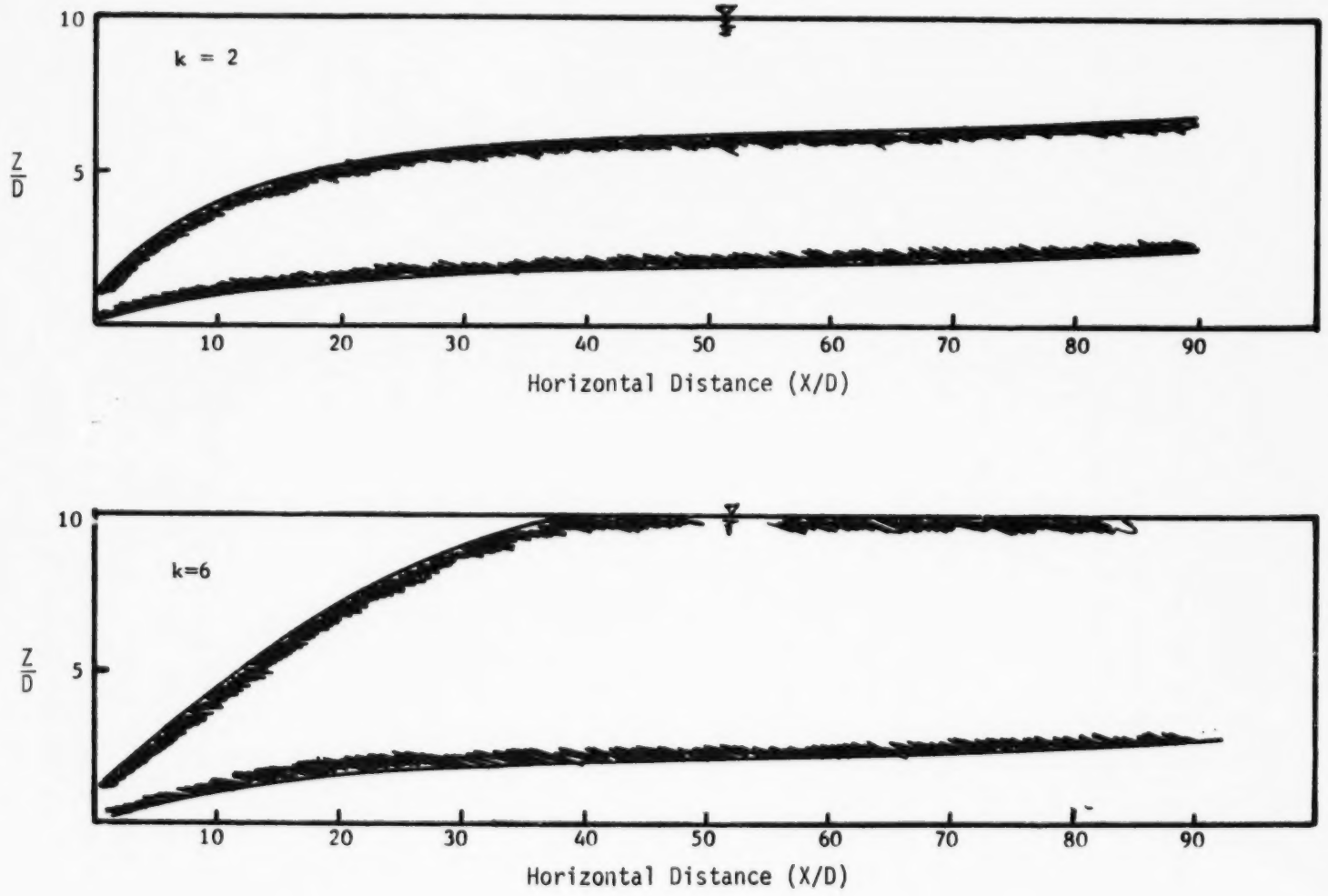

FIGURE 26. Effect of Ambient Velocity on Plume Spread: θ=15°, F=37.

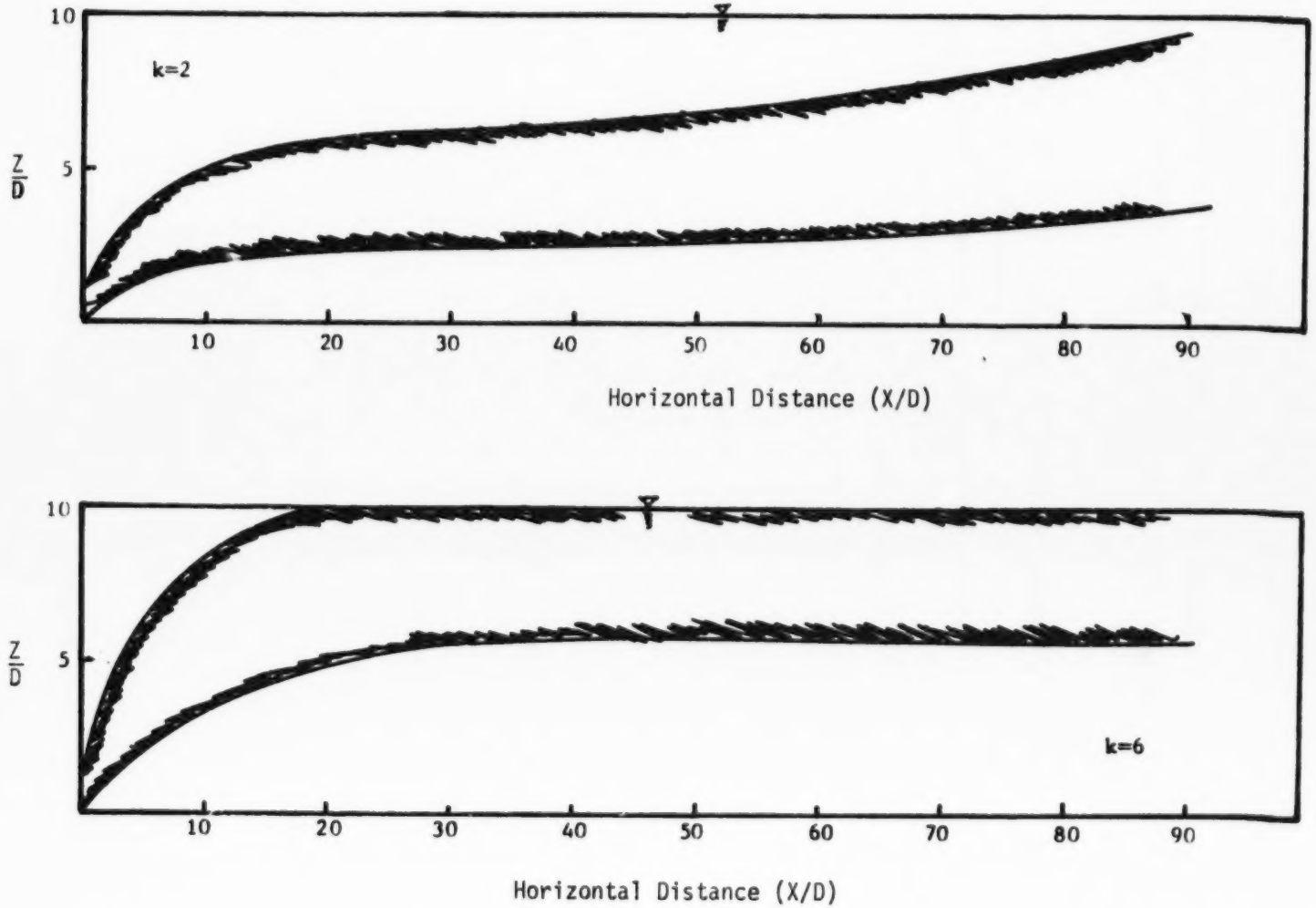

FIGURE 27. Effect of Ambient Velocity on Plume Spread: Θ=45°, F=37.

Figures 28 and 29 exemplify this result for an angle of 45° and F of 37. Data in the appendix indicates that in several instances the trend is less distinct.

In general, turbulence caused a slight spreading of the plume. However, the same observation is consistent with the decreased ambient velocity caused by the grid. A specific example is illustrated in Figure 2. The plume with turbulence is slightly wider than that without. Nevertheless, the altered trajectory might also be noted.

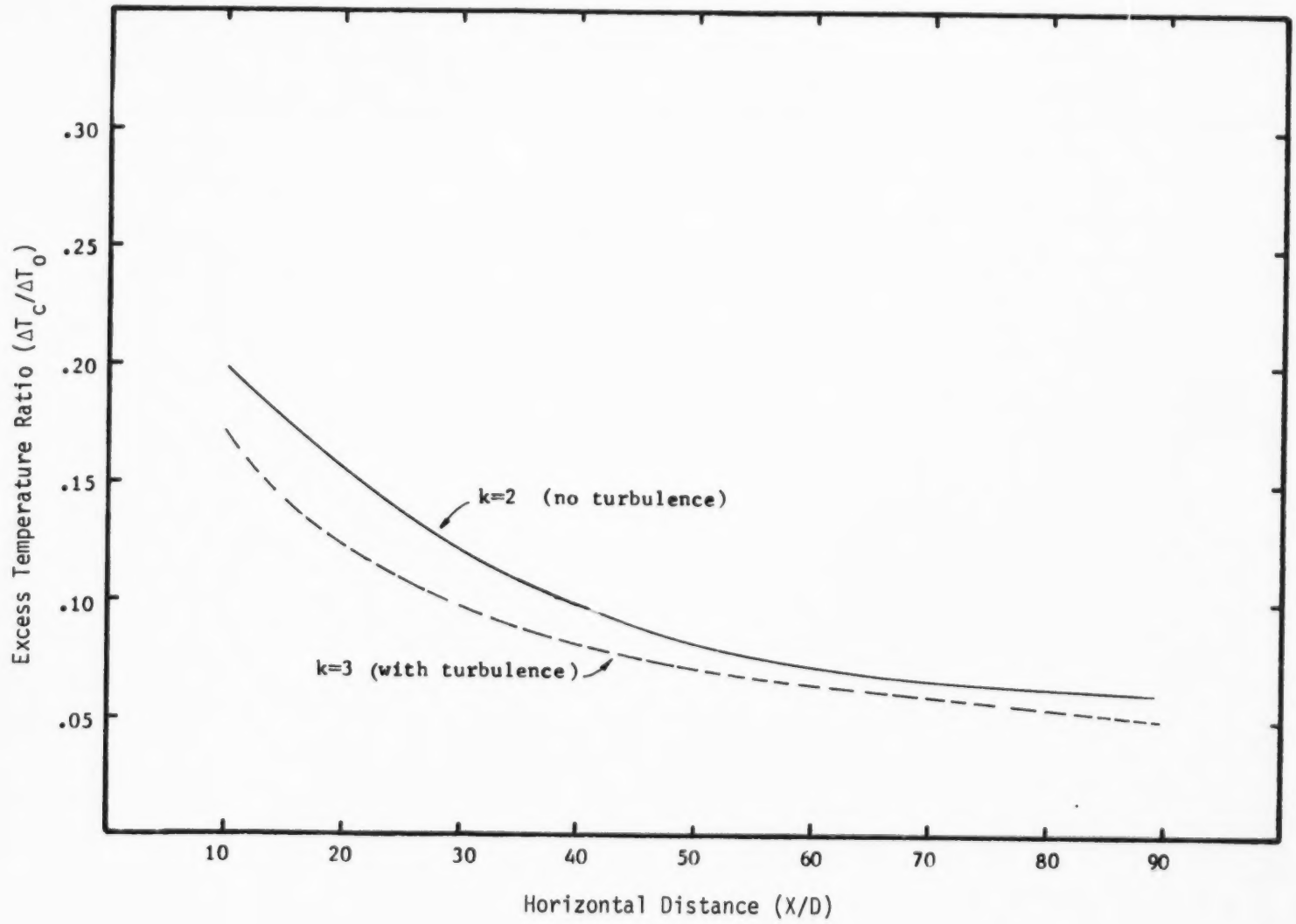

FIGURE 28. Effect of Turbulence on Temper ure - Velocity Relationship: Θ=45, F=37.

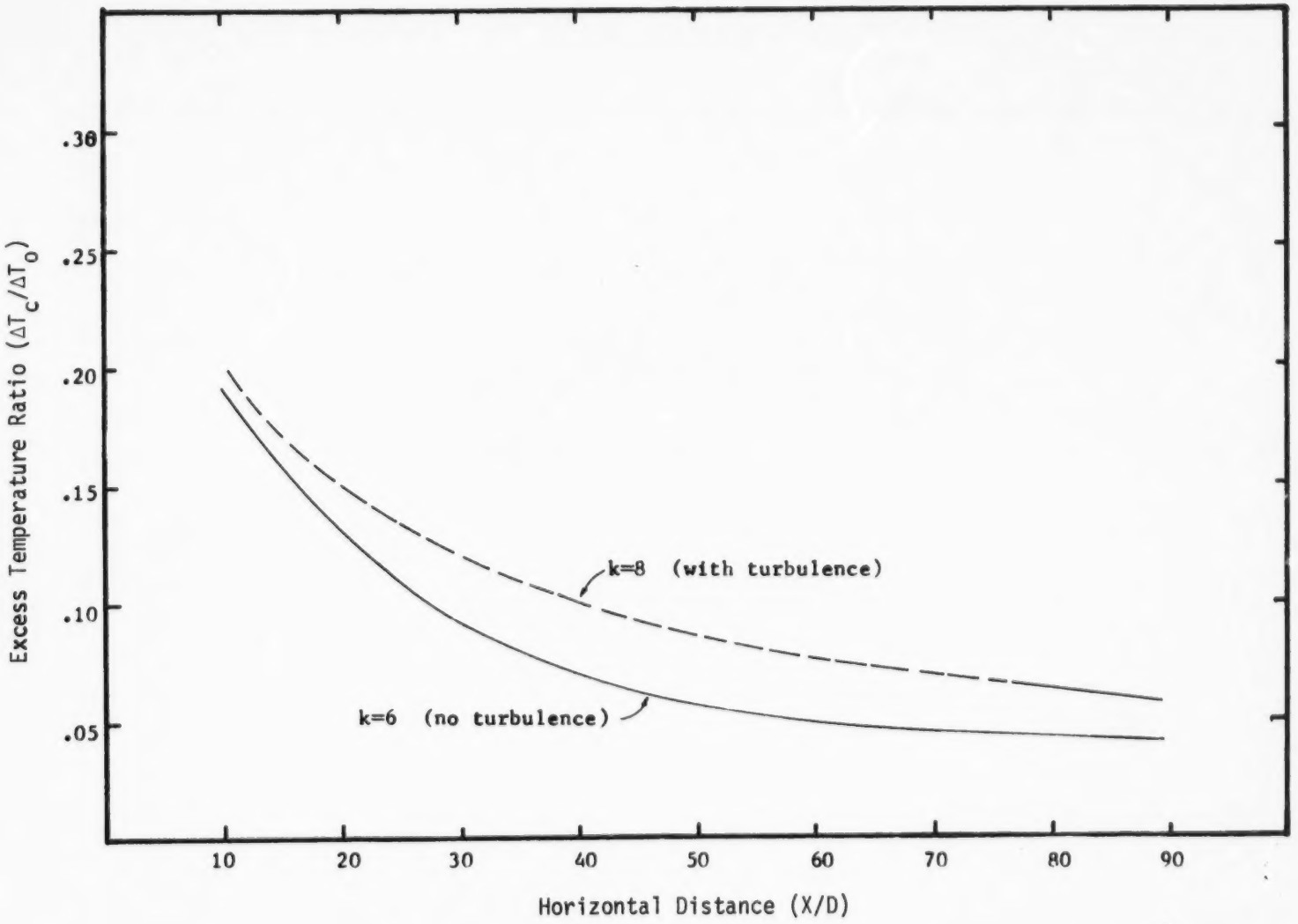

FIGURE 29. Effect of Turbulence on Temperature - Velocity Relationship: Θ=45°, F=37.

SECTION VI

REFERENCE

1. Shirazi, Mostafa A., and Davis, Lorin R., "Workbook of Thermal Plume Prediction, Volume I, Submerged Discharge," Environmental Protection Agency, EPA-R2-72-005a, August 1972.

SECTION VII

APPENDIX

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TABLE A-1. Plume Characteristics for Discharge Angle of 0°

X/D	No Turbulence				With Turbulence			
	F = 12		F = 37		F = 12		F = 37	
	k=2	k=6	k=2	k=6	k=2.7	k=7	k=3	k=8
Peak Temperature ($\Delta T_c/\Delta T_o$)								
10	0.47	0.50	0.54	0.54	0.45	0.49	0.53	0.54
20	0.31	0.295	0.38	0.36	0.275	0.31	0.33	0.335
30	0.23	0.205	0.29	0.24	0.20	0.20	0.245	0.22
40	0.18	0.16	0.23	0.175	0.155	0.15	0.185	0.16
60	0.13	0.11	0.145	0.115	0.10	0.105	0.125	0.11
90	0.08	0.07	0.115	0.08	0.065	0.075	0.075	0.085
Vertical Trajectory (Z/D)								
10	0.6	0.6	0.6	0.5	0.6	0.7	0.6	0.6
20	0.8	0.8	0.6	0.6	0.6	0.9	0.6	0.6
30	1.0	1.0	0.6	0.6	0.8	1.1	0.6	0.6
40	1.2	1.3	0.7	0.7	1.0	1.5	0.5	0.6
60	1.7	2.0	0.8	1.0	1.7	2.5	0.6	0.7
90	3.0	3.5	1.0	1.6	3.9	5.6	0.9	0.9
Plume Width (W/D)								
10	2	3	2	2.5	2.5	3	2	3
20	3	4	2.5	3	3	4	2.5	3.5
30	3.5	5	2.5	3.5	3.5	5	3	4
40	4	6	3	4	4.5	7	3.5	4.5
60	5	8.5	3.5	4.5	5	10	4	4.5
90	5.5	9	4	5	6	10	4	6

TABLE A-2. Plume Characteristics for Discharge Angle of 15°

X/D	No Turbulence				With Turbulence			
	F = 12		F = 37		F = 12		F = 37	
	k=2	k=6	k=2	k=6	k=2.7	k=7	k=3	k=8
Peak Temperature ($\Delta T_c/\Delta T_o$)								
10	0.35	0.425	0.365	0.47	0.355	0.43	0.385	0.51
20	0.19	0.21	0.20	0.255	0.16	0.22	0.20	0.255
30	0.14	0.155	0.155	0.16	0.115	0.165	0.135	0.17
40	0.11	0.11	0.13	0.115	0.09	0.13	0.10	0.125
60	0.08	0.08	0.10	0.07	0.065	0.09	0.075	0.09
90	0.065	0.06	0.08	0.06	0.05	0.06	0.06	0.07
Vertical Trajectory (Z/D)								
10	2.5	3.5	2.5	3.1	3.2	4.0	3.0	3.8
20	3.3	6.1	3.1	4.9	4.5	7.2	3.7	6.0
30	3.8	8.0	3.6	6.4	5.7	9.6	4.1	8.0
40	4.0	9.2	3.9	7.2	6.6	10.0	4.2	10.0
60	4.6	10.0	4.2	8.8	8.0	10.0	4.4	10.0
90	5.8	10.0	4.8	10.0	9.5	10.0	4.4	10.0
Plume Width (W/D)								
10	3	4	2.5	3.5	3.5	4	3	4
20	4	5.5	3.5	5.5	5	6.5	4	6.5
30	4	6	4	8	6	5.5	5	8.5
40	4.5	6	4	8	7.5	4	5.5	8
60	5	3.5	4	8.5	6	3.5	6	8
90	5	3	4	8.5	7	3	6.5	7.5

TABLE A-3. Plume Characteristics for Discharge Angle of 45°

X/D	No Turbulence				With Turbulence			
	F = 12		F = 37		F = 12		F = 37	
	k=2	k=6	k=2	k=6	k=2.7	k=7	k=3	k=8
Peak Temperature ($\Delta T_c/\Delta T_o$)								
10	0.19	0.20	0.20	0.19	0.16	0.215	0.17	0.265
20	0.135	0.13	0.15	0.125	0.105	0.155	0.13	0.175
30	0.10	0.09	0.12	0.095	0.08	0.115	0.10	0.125
40	0.08	0.065	0.10	0.07	0.065	0.095	0.085	0.10
60	0.065	0.045	0.075	0.05	0.05	0.07	0.065	0.085
90	0.05	0.035	0.06	0.035	0.04	0.065	0.05	0.05
Vertical Trajectory (Z/D)								
10	3.0	7.9	3.2	6.5	4.9	9.4	4.4	9.4
20	4.4	10.0	4.0	9.5	6.0	10.0	5.6	10.0
30	5.2	10.0	4.5	10.0	6.4	10.0	6.2	10.0
40	5.5	10.0	4.9	10.0	6.7	10.0	6.6	10.0
60	6.0	10.0	5.5	10.0	7.5	10.0	7.3	10.0
90	7.0	10.0	6.1	10.0	9.0	10.0	9.5	10.0
Plume Width (W/D)								
10	3.5	6	3	4.5	4	5.5	4	6
20	4	5	3.5	6	6	3.5	5	4
30	4.5	4	3.5	4.5	6	2	6	3
40	5.5	2.5	4	4.5	6.5	2.5	6.5	3
60	5.5	2	4.5	4.5	6	3	7	3
90	6	2	5	4	5.5	3	6.5	3

TABLE A-4. Plume Characteristics for Discharge Angle of 90°

X/D	No Turbulence				With Turbulence			
	F = 12		F = 37		F = 12		F = 37	
	k=2	k=6	k=2	k=6	k=2.7	k=7	k=3	k=8
Peak Temperature ($\Delta T_c/\Delta T_o$)								
10	0.14	0.135	0.16	0.13	0.14	0.14	0.15	0.175
20	0.09	0.06	0.11	0.08	0.095	0.105	0.105	0.105
30	0.07	0.035	0.08	0.055	0.07	0.09	0.08	0.075
40	0.06	0.025	0.06	0.04	0.06	0.085	0.065	0.055
60	0.05	0.015	0.045	0.03	0.05	0.075	0.05	0.05
90	0.04	0.01	0.04	0.02	0.04	0.07	0.04	0.045
Vertical Trajectory (Z/D)								
10	3.4	10.0	3.5	10.0	4.4	10.0	4.4	10.0
20	4.4	10.0	4.3	10.0	6.0	10.0	5.6	10.0
30	5.7	10.0	4.8	10.0	7.1	10.0	6.4	10.0
40	6.2	10.0	5.1	10.0	7.9	10.0	6.9	10.0
60	6.6	10.0	5.6	10.0	9.1	10.0	7.7	10.0
90	7.8	10.0	6.3	10.0	10.0	10.0	8.2	10.0
Plume Width (W/D)								
10	4.5	4	4	5	6	3	5.5	4
20	4.5	3	4.5	4	6.5	2.5	6	3
30	5	2	5	4	8	2.5	7	2.5
40	5.5	2.5	5	5	7.5	2.5	7	3
60	6	2	5.5	4.5	6	2.5	6.5	3.5
90	6	2	6	4.5	5.5	3	6.5	3

TABLE A-5. Plume Characteristics for Normal Discharge Angle.

X/D	No Turbulence				With Turbulence			
	F = 12		F = 37		F = 12		F = 37	
	k=2	k=6	k=2	k=6	k=2.7	k=7	k=3	k=8
Peak Temperature ($\Delta T_c/\Delta T_o$)								
10	0.14	0.14	0.225	0.155		0.125	0.18	0.13
20	0.11	0.12	0.155	0.115	0.13	0.10	0.135	0.11
30	0.09	0.095	0.125	0.09	0.085	0.085	0.105	0.09
40	0.07	0.075	0.105	0.075	0.065	0.08	0.09	0.08
60	0.05	0.06	0.08	0.06	0.045	0.07	0.065	0.06
90	0.03	0.05	0.065	0.045	0.03	0.05	0.04	0.05
Vertical Trajectory (Z/D)								
10	2.	3	1.2	3	2.5	5	2.3	4.4
20	2.6	3.7	1.7	3.5	3.4	5.7	3.6	5
30	2.9	4.1	2	3.5	4.3	7	4	5.1
40	3	4.5	2.2	3.5	4.9	7	4.3	5.2
60	3.4	5.2	2.3	3.5	5.9	7	5	5.5
90	4.6	7.2	2.5	4	6.5	9	7	7
Plume Width (W/D)								
10	3.5	5.5	4	5	4.5	6	4.5	6
20	4	7.5	4.5	6.5	5	7.5	5.5	8
30	4	9	4.5	7.5	5.5	6.5	6	8.5
40	4	9.5	5	8.5	6.5	8.5	6.5	8.5
60	4.5	9	5	8	7	8	6.5	9
90	5	8	5	8	7	7.5	7	8